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SATISFYING NAVAL LOW DATA RATE MOBILE COMMUNICATION REQUIREMENTS

By

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This thesis first examines the process for developing requirements and how they relate to the military acquisition and system engineering processes. Established methods for documenting satellite communications requirements are also reviewed. Next, potential technological drivers for a system to satisfy the low data rate needs of tomorrow's Naval Forces are presented. Current systems and plans are examined to provide information on current capabilities. Following that, a set of future architecture options and tradeoffs are presented to satisfy these mobile communications needs. Finally, conclusions and recommendations about the organizations and groups tasked with guiding the military and its use of space are provided.

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SATISFYING NAVAL LOW DATA RATE MOBILE COMMUNICATION REQUIREMENTS

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Submitted in partial fulfillment of the
requirements for the degree of

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In today's electronic age, the Department of Defense is relying more heavily on the transfer of information to maintain battlespace awareness and command and control efficiency. Current military satellite communication systems are unable to keep pace with the growing requirements for electronic transfer of voice, data, and video information. Additionally, these systems are expected to begin failing in the 2003 to 2007 timeframe with no identified replacement. Naval Forces consist of highly mobile units that often operate in harsh environments. New communication systems must be designed that can satisfy the needs of these mobile forces that cannot rely on secure landlines for the timely transfer of information.

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LIST OF ACRONYMS

ACAT	Acquisition Category
ADNS	Automated digital Network system
ARG	Amphibious Readiness Group
ATM	Asynchronous Transfer Mode
CAE	Component Acquisition Executive
COTS	Cost–Off-the-Shelf
CRD	Capstone Requirements Document
DAB	Defense Acquisition Board
DAMA	Demand Assigned Multiple Access
DISA	Defense Information Systems Agency
DISN	Defense Information Systems Network
DoD	Department of Defense
DSCS	Defense Satellite Communication System
DUSD	Deputy Under Secretary of Defense
ERDB	Emerging Requirements Database
FRD	Functional Requirements Document
GEO	Geosynchronous Orbit
HEO	Highly Elliptical Orbit
ICDB	Integrated Communications Database
INMARSAT	International Maritime Satellite
IPT	Integrated Product Team
ISDB	Integrated Satellite Communications Database
ITU	International Telecommunications Union
JMCOMS	Joint Maritime Communications Strategy
JROC	Joint Requirements Oversight Council
LDR	Low Data Rate
LEO	Low Earth Orbit
LPI	Low Probability of Intercept
MDR	Medium Data Rate
MEO	Medium Earth Orbit
MNS	Mission Need Statement

MSS	Mobile Satellite System
MUS	Mobile Users Study
ORD	Operational requirements document
PCS	Personal Communication System
PM	Program Manager
PSTN	Public Switched Telephone Network
OSA	Office of the Space Architect
UAV	Unmanned Aerial Vehicle
UFO	UHF Follow-On Satellite Constellation
USD (A&T)	Under Secretary of Defense for Acquisition and Technology

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I. INTRODUCTION AND DEFINITIONS

A. PURPOSE

Today, the military forces of the United States must operate in an increasingly *joint* environment in order to extend combat effectiveness. According to Joint Pub 1 [Ref. 1] , "The joint campaign plan achieves sequenced and synchronized employment of all available land, sea, air, special operations and space forces - orchestrating the employment of these forces in ways that capitalize on the synergistic effect of joint forces." Furthermore, Chairman of the Joint Chiefs of Staff General John M. Shalikashvili has stated that "command, control, communications and computer (C4) networks and systems provide the means to synchronize joint forces." [Ref. 2] In order to carry out this role, "C4 systems must provide the rapid, reliable, and secure flow and processing of data to ensure continuous information exchange throughout the force," according to Joint Pub 6-0 [Ref. 3]. In today's electronic world, this means that open communication channels must be maintained in order to facilitate this information flow.

Many military units are able to maintain communications through the use of high bandwidth fiber optic cable and large satellite receivers, capable of utilizing landbased communications infrastructure and geosynchronous orbiting satellite communications constellations. Other units must rely upon lower bandwidth antennas and radios for processing terrestrial based line-of-sight communications. This puts the user at a disadvantage from the perspectives of both sending and receiving battlespace awareness information.

United States Naval operational forces are comprised largely of highly mobile units. These units include ships at sea, aircraft, wheeled units such as Armored Personnel Carriers, and ground units such as infantry platoons and Special Operations Forces. In order to participate in the joint campaign envisioned in today's Joint Pub doctrine, these forces require an effective communications network that will allow them to participate in the two-way flow of information.

This thesis will examine the need for, and the technical limitations on a military operated system capable of satisfying the low data rate mobile communications requirements of Naval Forces for the 2010 timeframe, and present architecture options for consideration. Because current military owned satellite communications systems are due

to reach the end of their planned life-cycle in the 2003-2007 timeframe, now is the time to begin investing in the next generation of capabilities. [Ref. 4]

Discussion will begin with the requirements generation process and how it applies to this problem. Next, current capabilities will be examined in terms of both current military satellite communication (MILSATCOM) systems, and satellite communication terminals in the military inventory. This will be followed by an examination of the vulnerabilities and limitations of current generation satellite communication systems. Finally, various architecture proposals will be offered as potential solutions to the mobile communication problem.

B. DEFINITIONS

Different services, and even different agencies within the same service, often work with a variety of definitions for the same terms. To avoid confusion, this section will provide background discussion on specific terms relevant to this thesis. This is not to say that other definitions are incorrect, but rather to provide a clear understanding to the reader of the context under which this research was conducted.

1. Mobile

Webster's New World Dictionary defines a military usage definition for the word *mobile* as "capable of being moved quickly and easily." [Ref. 5] Many defense satellite communications systems fit this description. They range in size from small hand-held parabolic dish antennas to large satellite dishes that can be towed by truck. However, they must be set up at a stationary location in order to establish the pointing accuracy necessary to provide a communication link. This may be acceptable for some land-based forces, but remains insufficient for shipboard and aircraft applications.

The term *mobile* for this document will instead be used to denote a "communication on the move" capability. This will include ships, aircraft, wheeled vehicles and any other application that will allow personnel to communicate without having to stop and setup antennas or other hardware. Instead, these units will be able to communicate while travelling at speeds from a slow walk, to multi-mach aircraft.

2. Low Data Rate

Data rate refers to the speed at which bits are transferred across a channel in a digital communication system. This thesis will be concerned primarily with voice, and some data applications that do not need the large volume of information required for uses such as video transfer. This is an effort to satisfy requirements for the most disadvantaged user, the hand-held, or man pack terminal that is limited in size, weight and processing capability due to mobility requirements and ruggedness of construction.

The human voice channel is generally described as operating in the range of 300 Hz to 4 kHz, based on both frequencies transmitted and frequency response of the human ear. According to the Nyquist sampling theorem:

> If a band-limited signal is sampled at regular intervals of time, and at a rate equal to or higher than twice the highest significant signal frequency, then the sample contains all of the information of the original signal. [Ref. 6]

Applying the Nyquist sampling theorem to a voice channel with a highest significant signal frequency of 4 kHz, yields a sampling rate of 8 kHz, or one sample every 125 μs. Each sample must now be quantized and coded into a binary representation for transmission.

Many practical digital pulse code modulation (PCM) systems today use a 7 or 8 bit binary code. The latter case provides 2^8, or 256 discrete steps to quantize, or represent, the amplitude of each voice sample. These quantized levels generally provide a non-linear representation of each sample in order to provide higher resolution in the frequency ranges where most voice information is contained, while still providing representation of frequency ranges that occur less often. This non-linear representation is known as companding. [Ref. 6]

An 8 bit representation of a signal sampled at 8 kHz produces a data rate of 64 kbps for full voice band capability. This represents the upper limit of the low data rate definition for this document. By taking advantage of redundancy and predictability in speech sounds, encoding devices can be used to compress a voice channel down to 9.6 kbps, while maintaining signal quality. Most military satellite voice communications today accept quality degradation by operating at 2.4 kbps or 4.8 kbps. These lower data

rates provide adequate information exchange, but limit such features as voice and inflection recognition. Some modern MILSATCOM systems consider 4.8-64 kbps medium data rate, but in this document they will be considered low data rate.

II. REQUIREMENTS ANALYSIS

The first step in any system development is to determine the requirements that the system must satisfy. This is the least understood activity in the development process, yet can have the largest impact on the final product. Requirements are the user's way of communicating needs to the designer. They define *what* the problem is, not *how* to solve it. They include such parameters as the environment in which the system must perform, objectives the system must satisfy, and any desired constraints. [Ref. 7]

A. REQUIREMENTS BACKGROUND

Requirements come in three basic types, with increasing resolution. Functional requirements define the necessary tasks that a system must perform in general terms. Performance requirements express quantifiable descriptions of how the system must satisfy its required tasks. They are commonly expressed in such common terms as speed, weight, timing, size, or area coverage. The final type, design requirements, delineates "build-to" requirements that define manufacturing processes, or specific hardware and software descriptions. [Ref. 8]

Regardless of type, a well designed requirement will posses meaningful attributes. Most importantly, a requirement must be verifiable in order to substantiate compliance. This means that ambiguous terms such as excessive, sufficient, or resistant must be avoided. Instead, specific quantitative language must be used to express characteristics that can be measured and tested. Additionally, each requirement must take into account all intended mission profiles, operations and maintenance concepts, operational environments, and outside constraints. Finally, each requirement must be consistent with all other requirements, and present an appropriate level of resolution commensurate with its level in the system hierarchy. [Ref. 7]

Defining system requirements is not a one-time event, but an iterative process that must continue throughout a product's life-cycle. In fact, user needs are seldom clearly defined. Instead, the user must work closely with all disciplines that are impacted a system during its life-cycle to continually validate and refine all requirements. A failure to aggressively attack the requirements definition problem early results in an incomplete understanding of requirements, and leads to the problem of building the wrong system, one that does not satisfy the user's needs when fielded.

Inadequate requirements analysis early in a program can lead to one of two situations. The first is cost overrun. This occurs when requirements are poorly defined, presenting a lack of clear direction to the developing command or agency. Results are often a system that fails to adequately meet the user's needs, or is not operationally effective or suitable for the intended operating environment. This leads to frequent redesign, schedule slips, poor performance, and higher program costs.

Another result of insufficient requirements analysis is cost growth. This occurs when new requirements are added late in the development process. Growth differs from overrun in that the new requirements often necessitate contract renegotiations to reflect changes leading to major system redesign, in effect creating a new system. In some cases, the new requirements may invalidate a large and expensive portion of any development already undertaken.

This does not mean that requirements analysis should be completed early, and decisions locked in for the life of the program. It does no good to field a system following a long development process if that product is no longer of any operational significance. Instead, requirements must be responsive to changing circumstances such as technology and threat assessments, while taking into account the trade-offs between cost and need, as well as performance and effectiveness.

B. DEPARTMENT OF DEFENSE ACQUISITION PROCESS

The Department of Defense is charged with the procurement and life-cycle care of many complex systems. Costs for these systems range into the billions of dollars and are a significant drain on the Department's budget. With available dollars declining and systems complexity and expenses growing, the Department has been forced to impose controls on its acquisition efforts in order to contain costs and minimize waste.

Prior to 1990, the United States existed in a world dominated by Cold War politics. The Department of Defense (DoD) benefited from this situation in the form of increasing budgets and seemingly limitless weapons programs when compared to today's standards. Additionally, the various military services operated nearly autonomously with little capability to conduct coordinated warfare. This situation led to the procurement of stovepipe systems that were developed independently, often duplicated functions, and were unable to operate in a common environment. New legislation attempted to end this predicament in 1986 with passage of the Goldwater-Nichols Act.

The Goldwater-Nichols Defense Reorganization Act of 1986 is a legal attempt to tear down the walls between the military services. It mandated a new structure within the Department of Defense that now places greater authority with the Chairman of the Joint Chiefs of Staff, as well as with the Unified and Specified Commanders. This Act also mandated changes in the Department of Defense's acquisition process by forcing major acquisition programs to compete and perform in a joint environment. Today, instead of operating independently of each other, the services must work and fight together, as well as develop warfare systems that are interoperable. To meet this end, the acquisition process has been formalized under the guidance of the Under Secretary of Defense (Acquisition and Technology) (USD(A&T)) with military support led by the Vice Chairman of Joint Chiefs of Staff (VCJCS). [Ref. 9]

The USD(A&T) is responsible for all major acquisition programs from each of the services. He performs his duties by issuing directives and regulations, and through his role as head of the Defense Acquisition Board. The primary directives are contained in the Department of Defense 5000 series instructions. These documents have been in existence for many years, but recently revised to reflect major reforms of acquisition policy in order to streamline the process. [Ref. 8]

The Defense Acquisition Board (DAB) is the body responsible for advising the USD(A&T) in his capacity as authority for oversight and approval of major DoD programs. Under recent reforms, every acquisition program for which the DAB is responsible is assigned an Integrated Product Team (IPT) comprised of OSD level personnel, DAB members, and service or Program Office representation. This interdisciplinary panel works with the Program Manager (PM) to guide the program through its development and production phases, while ensuring that cost, schedule and performance objectives are met. Decisions that cannot be reached by the IPT are brought to the attention of the full DAB for resolution. [Ref. 8]

The VJCS position was created by the Goldwater-Nichols Act [Ref. 9]. Among the primary duties of this office are Vice-Chairmanship of the DAB, and Chairmanship of the Joint Requirements Oversight Council (JROC). Under his leadership, the JROC, comprised of the Vice-Chiefs of the military services, is tasked with validation of warfighting requirements proposed by the services and assessing joint potential of any possible acquisition program. [Ref. 9]

Requirements are submitted to the JROC in the form of a Mission Need Statement (MNS). This document is a brief declaration of a new mission area or identified

capability deficiency produced in response to a validated threat to the United States or its military forces. Attempts must first be made to satisfy this need through non-material solutions such as changes in tactics or doctrine. If this type of solution is not feasible, then the component command must assess the potential scope of any material solution. Only those MNS's expected to lead to a procurement program exceeding certain spending limits, or expected to generate significant political interest are presented to the JROC. Others are handled by individual services. If the MNS is approved by the JROC, it is then submitted to the DAB to be considered for program establishment and funding. [Ref. 10]

Department of Defense Directive 5000.1 (DoD Directive 5000.1), "Defense Acquisition," and Department of Defense Regulation 5000.2-R (DoD 5000.2-R), "Mandatory Procedures for Major Defense Acquisition Programs (MDAPs) and Major Automated Information System (MAIS) Acquisition Programs," exist as the written authority from the Secretary of Defense for all DoD acquisition programs. In accordance with these documents, all DoD acquisition programs are assigned an acquisition category (ACAT) designation as outlined in Table 1. Those programs expected to meet ACAT I criteria are reviewed by the DAB, other programs are sent to their respective services for consideration. Once the DAB receives a MNS from the JROC that is expected to require an ACAT I designation, a Milestone 0 decision must be made. [Ref. 8,11]

Category	Description
ACAT I	Major Defense Acquisition Programs (MDAPs) estimated by the USD(A&T) to require expenditure for research, development, test and evaluation of more than $355 million, or procurement of more than $2.135 billion (in FY 1996 constant dollars). Other programs can be designated as ACAT I at the discretion of the USD(A&T).
ACAT ID	ACAT I programs for which milestone decision authority rests the USD(A&T).
ACAT IC	ACAT I programs for which milestone decision authority rests the service Component Acquisition Executive (CAE).
ACAT IA	Programs for Major Automated Information System (MAIS) acquisition.
ACAT II	Major systems that do not meet the criteria for ACAT I and are managed by the cognizant CAE. These systems are estimated to cost more than $300 million in FY 1980 constant dollars, or are designated by the CAE as ACAT II programs.
ACAT III	These are programs that do not meet the requirements to be designated as ACAT I or ACAT II. The milestone decision authority my be delegated to the lowest possible level by the CAE.

Table 1 - DoD Acquisition Categories

Milestone 0 is the first step in the life of an acquisition program. It marks entry into Phase 0 of the acquisition process, also known as Concept Exploration. This can be considered a transition from the initial requirements generation process, to acquisition management. At this point a Program Office, headed by a Program Manager (PM) is generally established to manage all phases of the acquisition process as outlined in Table 2 [Ref. 8].

PHASE	NAME	DESCRIPTION
0	Concept Exploration (CE)	• Evaluate feasibility of alternative concepts • Determine most promising concepts or solutions
I	Program Definition and Risk Reduction (PDRR)	• Design the system • Demonstrate critical processes and technologies
II	Engineering and Manufacturing Development (EMD)	• Mature and finalize selected design • Validate manufacturing and production processes • Test and Evaluate the system
III	Production, Fielding/ Deployment and Operational Support (PF/DOS)	• Produce and field/deploy the system • Monitor system performance • Support fielded system • Modify or upgrade the system as required

Table 2 - Acquisition Process Phases

Entry into each phase is preceded by a milestone decision, made by the cognizant Milestone Decision Authority. These decisions are made to monitor progress in the areas of cost, schedule and performance, and to set criteria to be met for completion of the next phase. In the case of ACAT ID programs, this decision is made by the USD(A&T), and for ACAT IC programs, the decision is made by the CAE. [Ref. 8]

A major product of the Concept Exploration phase is an initial Operational Requirements Document (ORD). Developed primarily by the user of the system under development, it is initially a broad statement of operational performance parameters to be satisfied by the system. The ORD is used to define objective performance as well as minimum acceptable thresholds. This is the guiding document for system development and continues to evolve along with the system. As potential trade-offs are examined, and the system proceeds through its lifecycle, the ORD is continually refined to reflect the status of threats, technology, budgets and other factors that play into the acquisition

process. It is in this process of creating and refining the ORD that arriving at a thorough understanding of system requirements is critical. [Ref. 10]

C. SYSTEM ENGINEERING PRINCIPLES

Today's military systems are increasingly complex interactions between hardware and software components. Because of this, greater emphasis has been placed on the discipline of system engineering to aid in the design and production of new systems. The Defense Department's publication MIL-STD-499A defines systems engineering as:

> ...the application of scientific and engineering efforts to (a) transform an operational need into a description of system performance parameters and a system configuration through the use of an iterative process of definition, synthesis, analysis, design, test, and evaluation; (b) integrate related technical parameters and ensure compatibility of all physical, functional, and program interfaces in a manner that optimizes the total system definition and design; (c) integrate reliability, maintainability, safety, survivability, human engineering, and other such factors into the total engineering effort to meet cost, schedule, supportability, and technical performance objectives. [Ref. 12]

Systems Engineering can also be described as the process of applying an organized approach to solving a complex design problem. Although varied in application, the goal is the same, to produce an efficient system that satisfies a need, within the constraints of cost, schedule and performance.

Systems Engineering is a process that is continually applied throughout a system's life-cycle, from requirements definition to disposal. It gathers together people from all disciplines that have a hand in any life-cycle phase in an attempt to uncover the hidden requirements that enable creation of an elegant system that will satisfy all needs and constraints.

While still concerned with the details of a system, Systems Engineering is primarily concerned with the macro level of the system. The Systems Engineering process is aimed at managing the "forest" and letting more specialized teams build the "trees," although each level in the design has its own "forest" to which the principles of Systems Engineering must be applied.

The people primarily responsible for conduct of the Systems Engineering process are the Systems Engineers. They work throughout a system life-cycle to provide the best possible product to solve a given problem. Systems Engineers do this by taking an outside look at their area of responsibility, or subsystem, and seeing how this part of the problem must interact with all other parts of the problem, and designing to maximize performance of the entire system over this subsystem.

All participants in a project bear the responsibilities of Systems Engineering. Each person will have their own area of expertise, and must use that knowledge to design the interfaces and attributes that will allow their part to be a piece of an efficient whole. This requires cooperation as opposed to competition among all people involved.

In order to perform this job more effectively, formal processes have been established. The DoD's formal systems engineering process is detailed in Figure 1 [Ref.13]. This process is depicted as an iterative loop in which four procedures are performed on inputs to produce an output. The inputs to this process are the user's requirements, and the output is a system that will satisfy these requirements.

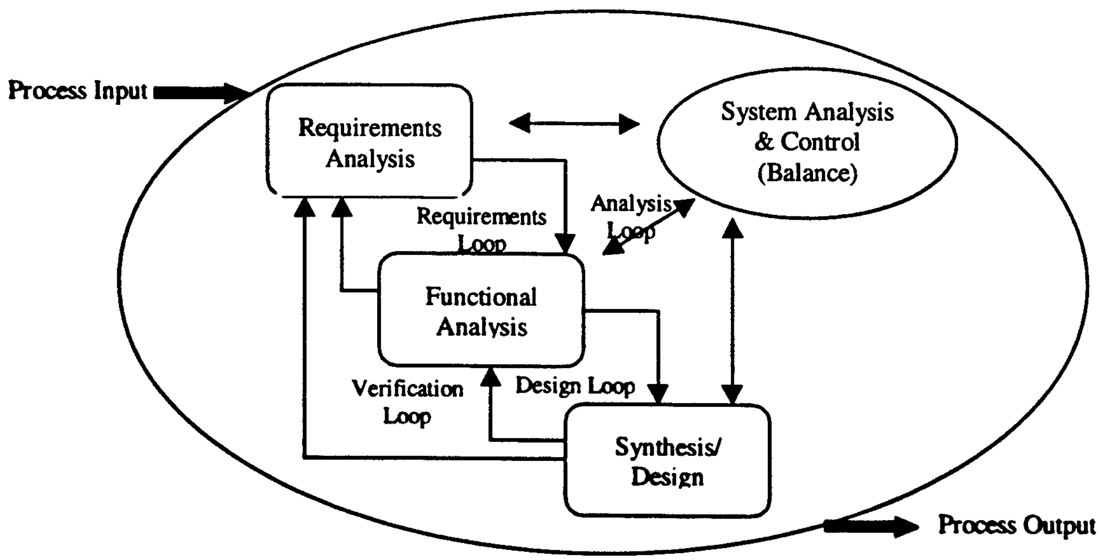

Figure 1 - The DoD Systems Engineering Process [Ref.13]

User requirements are generally presented as a set of broadly defined top-level performance parameters. They need to present the problem to the system engineer without unnecessarily restricting the solution. The system engineer must then work with the user, designer, manufacturer, logistician, and any other discipline that will be a part of

the system life-cycle to further refine these requirements and develop architecture options and trade-offs.

D. MILSATCOM MISSION NEEDS STATEMENT

The Commander in Chief of United States Space Command is the specified commander responsible for U. S. military support from the space environment. In this capacity he published the *Mission Needs Statement For Follow-On Military Satellite Communications* in 1995. This MNS documents a requirement to maintain a satellite communication system to support mission areas detailed in the Defense Planning Guidance. [Ref. 14]

The eight page report uses broadly worded language to describe a satellite communication system for the future. It calls for a "system of systems" to satisfy wide ranging operational scenarios. This is an effort to force the interoperability of a disparate set of systems by building them to a shared standard, allowing users to access a range of systems using a common transceiver terminal. Accomplishing this would aid in minimizing system life-cycle costs, as well as reducing the user's maintenance and equipment load.

The MNS also recognizes the importance of commercial industry in providing communications services. Today's MILSATCOM systems do not posses the capacity to support demand. [Ref. 15] Commercially available services can be used without the long term costs of developing, designing, building, and maintaining a military owned system. It also notes that commercial services are seldom available globally, and do not necessarily provide features, such as netted communications and nuclear hardening, that military may need. Although, it does suggest that future military systems be designed to make use of commercial capacity when it is available.

Finally, it is prudent to note that in the author's opinion, this mission needs statement appears to have overstepped its bounds. This document violates the definition of a requirement presented earlier in this chapter by providing solutions to an operational need. This document specifies the use of satellites to solve the communication needs of the military rather than just describing the need, indicating that the decision makers have already decided how they wish to go about building a solution. This may be the result of carelessness in writing the MNS, but may also be that the United States Space Command is focused only on space based solutions, and ignoring other options.

E. MOP 37

In 1992, the Chairman of the Joint Chiefs of Staff released Memorandum of Policy No. 37 (MOP 37), titled Military Satellite Communications Systems. This document establishes policy, guidance, and responsibility for all phases of MILSATCOM, from requirements generation through system operation. MOP 37 recognizes the utility of SATCOM capacity, as well as the need to regulate and prioritize the use of this limited resource. [Ref. 16]

The stated objective of MOP 37 is "to ensure essential MILSATCOM support for mission accomplishment." A primary component of the document is a comprehensive listing of SATCOM related roles and responsibilities within the DoD. Key portions of these listings are those offices responsible for requirements. They include the Chairman of the Joint Chiefs of Staff (CJCS), the Commanders-in-Chief (CinCs) of the Unified and Specified commands, the Joint Staff, and the Director of the Defense Information Systems Agency (DISA).

CJCS has outlined his responsibilities as those of defining the process by which SATCOM requirements are documented, as well as approving those requirements. The CinCs are responsible for submitting consolidated and prioritized lists of requirements based upon subordinate command requirement submissions as well as periodic OPLAN reviews. The Joint Staff is tasked with managing the MILSATCOM requirements process as outlined by the CJCS. DISA is charged with maintaining an Integrated SATCOM Database (ISDB) which documents all approved SATCOM requirements. [Ref. 16]

Much like the MNS, MOP 37 appears to dictate specific material solution to a communication need. While this may be at least partially true, MOP 37 does recognize the existence of alternative solutions. In fact, DISA is further tasked with assessing the feasibility of satisfying requirements by MILSATCOM.

F. THE EMERGING REQUIREMENTS DATABASE

As previously discussed, DISA is tasked with maintaining an Integrated SATCOM Database which documents all approved SATCOM requirements. This is currently accomplished through the use of two separate databases, the Integrated Communications Database and the Emerging Requirements Database.

The Integrated Communications Database, or ICDB, contains near term requirements for MILSATCOM. The database information is classified Secret. Online access to the ICDB is provided by DISA via computer modem and PC based software. Access is limited to approved units that are authorized to provide direct inputs to the database. The software package allows these users to access the information contained in the database, submit new requirements, and communicate directly with DISA.

It was recognized that the ICDB, although necessary, was insufficient. Due to long satellite development and deployment lead times, as well as the explosive growth in technology capability, a method to capture requirements for farther into the future was needed. The Emerging Requirements Database (ERDB) was created in 1995 to satisfy this need.

The ERDB is a much less formal document. Its inputs are an attempt to capture predictions for ten years into the future based on what is known today. Unlike a more formal ORD, the purpose of this undertaking is to provide direction for long range planning guidelines to the agencies and personnel developing future SATCOM systems. There is currently no document defining the ERDB's structure or process. Naval inputs are provided by contacting the N52 branch of Naval Space Command, and furnishing them with a best guess of future needs. This information is cataloged, and periodically reviewed for consistency. As of this writing, Version Three is being prepared for release.

ERDB Version 2 is used as the basis of stating future Naval communications for this thesis. Appendix A contains an extract of the ERDB tables listing only low data rate requirements for Navy and Marine Corps Forces. Naval requirements are broken down by functional user needs into fleet command requirements, carrier battlegroup (CVBG) requirements, amphibious readiness group (ARG) requirements, and Marine Corps (USMC) requirements. [Ref. 17]

Within each ERDB table, every line item details an individual circuit requirement. Data rate, type of operation, availability, connectivity, level of protection, information type, and expected duty cycle are listed. Perhaps the most important attribute is listed last, requirement multiplier, or number of this circuit type required. This is primarily noticeable of the Fleet requirements list where 2000 point-to-point mobile satellite service circuits are required at 2.4 kbps!

The summary on each chart lists the total number of line item circuits, as well as their combined throughput. It does not, however, account for the requirements multiplier value assigned to each. On the CVBG requirements table, this drives the total number of

circuits from 23 to 46, and the combined data rate from 416 kbps to 1127.2 kbps, more than double the total throughput. These numbers can be somewhat tempered, however, by the fact that must duty cycles are significantly less than 100%. This means that many of these circuits are only active a small portion of the time, opening a the possibility of increasing the number of circuits allowed without out changing total capacity by sharing channels.

In the author's opinion, the ERDB is an excellent planning tool, but cannot be used as a standalone document. It is not reasonable to expect that a single carrier battlegroup or amphibious readiness group will be utilizing SATCOM assets at a point in time. Instead, operational tempo, deployment schedules, doctrine, and training needs must become part of the equation. Additionally, many smaller or independently operating units may be operating with SATCOM requirements.

Current thinking envisions a continuum running from peacetime operating scenarios, through humanitarian and peacekeeping missions, to two simultaneous major regional conflicts (MRC), each with greatly increasing communications needs. Also, the fact that the other services and national interests will have their own requirements for low data rate SATCOM must be included. A new system must be capable of satisfying these competing priorities under the worst case scenario of two MRCs.

G. THE CAPSTONE REQUIREMENTS DOCUMENT AND THE FUNCTIONAL REQUIREMENTS DOCUMENT

The ERDB is a good tool for grasping the actual numbers of circuits and volume of data requiring transfer via SATCOM or other mobile communications channel. It does not, however, address many of the larger issues that are of concern to military forces. These issues include operational concepts, and architectural concerns. To fill this gap, United States Space Command has compiled the *Capstone Requirements Document*, known as the CRD.

This document is designed to provide high level requirements and rationale for the entire MILSATCOM gamut. These include wide band and narrow band requirements. The CRD provides a checklist of characteristics which can be used to describe individual circuit requirements in more refined documents such as the ERDB. [Ref. 18]

To complement the CRD, Naval Space Command, the Navy's operational space command, has produced the Navy Functional Requirements Document (FRD). The FRD

complements the CRD by using elements of the latter document and applying them to Naval specific communication requirements. It is the high level document used to provide descriptive characteristics to Naval Force's ERDB inputs.

The FRD begins by describing current and planned MILSATCOM systems, covering space, control, and terminal segments, as well as services provided. An important part of this is the depiction of a fixed, limited bandwidth capability, in the face of exponentially growing demand for services. Systems already approved and developed for the DoD were designed prior to the Persian Gulf War, and the information explosion that followed, and they are due to reach the ends of their lifetimes within the next decade. As of this writing, no replacement has yet been identified.

Required characteristics are presented with broad definitions. These characteristics include protection, capacity, access, and flexibility. Protection refers to the ability to prevent the user from perceiving any service or security degradation due to the effects of physical destruction, nuclear detonation, jamming, or Information Warfare attacks. Capacity is the ability to provide the necessary information transfer when needed, to a wide range of users at increasingly lower echelons. Access is the ability to use the communication services when they are needed, with network control responsibilities delegated to the lowest appropriate level. Flexibility includes the capability of accessing SATCOM channels from any operational area where services are required, as well as the ability to trade protection features for capacity in a communication system that is path independent. These features combine to provide the set of high level requirements. [Ref.19] They are not verifiable requirements by themselves, but must be used to aid in defining attributes for lower level requirements. In fact, many of these descriptors are used to define ERDB line items in Appendix A.

Narrowband SATCOM is assigned a set of broadly defined attributes. First is the ability to provide service to mobile platforms. This includes users that fit within the definition provided in the first chapter of this thesis. Next is the fact that any narrowband system needs to be optimized for voice and LDR data. This provision is to stress the need for tactical command and control via voice circuits, as well as provide battlespace awareness via tactical data nets and broadcasts. Finally, flexibility must be built in as defined above, in order to provide the ability to tailor services to the operating environment.

The FRD presents a list of broadly stated emerging information requirements divided into functional categories. The ERDB refines these requirements into individual circuits. These categories are based on the principle of shrinking the OODA loop.

The OODA loop is an acronym for observe, orient, decide, and act. It represents a formalized model to represent a decision process as depicted in Figure 2. Shrinking the time to complete the loop, without losing quality in decision making, requires the timely and accurate flow of information. This will allow the strike planning process to be reduced from days to hours, and provide total battlespace awareness to all participants. [Ref. 19]

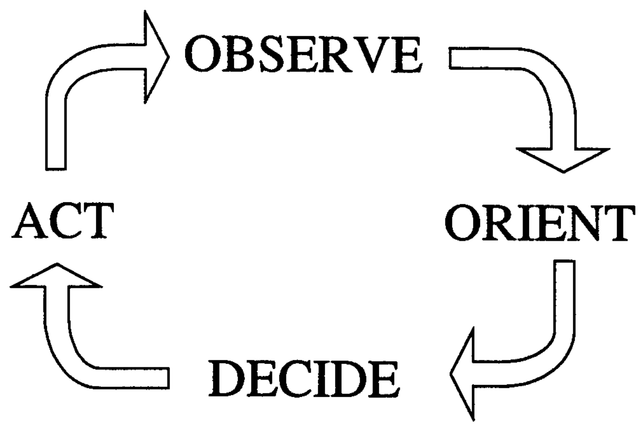

Figure 2 - The OODA Loop [Ref. 19]

In order to accomplish this, the FRD has defined seven emerging information requirements areas to be satisfied. Although each area can be satisfied using MILSATCOM networks, not all of them are best solved via LDR SATCOM. They all, however, must be accessible to mobile units in order to satisfy Naval requirements. The requirements are listed below.

- Full knowledge of the battlespace prior to engagement; optimize effectiveness of the attack; strategy, tactics, execution.
- Over-the-horizon control and feedback from advanced weapons.
- Over-the-horizon targeting links.
- Command and control of dispersed Marine units engaged in over-the-horizon amphibious operations.
- Improved computer-to-computer data links.
- Range extension of remote sensors.
- Extension of digital telephony services to more and smaller platforms.

In order to meet all of these articulated requirements, the FRD presents a space segment vision consisting of a multi-layered system of systems. The complete picture encompasses both military and commercially operated SATCOM assets working together. LDR assets would operate from low altitude, crosslinked satellites, to provide narrowband connectivity between mobile units, smart weaponry, remote sensors, and fixed sites to allow entry to the terrestrial communications grid. Assets at higher altitudes would provide higher capacity with increased protection. This configuration is envisioned as providing a high data throughput capability to small terminals. It would be designed to afford all of the protection and flexibility requirements laid out in this document.

Although the FRD does not provide the circuit resolution of the ERDB, it does provide much of the qualitative description of SATCOM requirements. These documents must be used together in order to get a more complete picture of future needs. The missing piece of the puzzle is still an operational loading assessment to determine total numbers of circuits and bandwidth needed to satisfy these requirements in the envisioned two MRC scenario. It must also be noted that like the previously discussed requirement sources, the FRD steps outside its bounds and presents an architectural solution. Those responsible for developing requirements must be careful not to unnecessarily restrain the set of possible solutions by presenting unrealistic or overly restrictive requirements. Give the developing agencies as much room as possible to work with.

H. MOBILE USERS STUDY

In 1996, the communications branch of Naval Space Command commissioned Booz, Allen & Hamilton, Inc. to conduct a MILSATCOM operational loading study. The study was set up to load ERDB requirements against MILSATCOM assets in a variety of operational scenarios, ranging from peacetime operations to conduct of one MRC and several lesser regional conflicts. Using Version One of the ERDB, the study revealed that 63% of UHF LDR MILSATCOM assets would be used, but nearly 100 communication network requirements would remain unsatisfied. Remaining capacity would not satisfy these requirements due to data rate incompatibility (remaining 4.8 kbps requirements are incompatible with current DAMA access scheme). Some of this could be solved by migrating requirements to EHF frequencies, but many mobile users are currently

incapable of using this portion of the spectrum. Furthermore, this only accounts for Naval requirements, and assumes that Naval Forces have access to 100% of the MILSATCOM capacity. In a more realistic scenario, other forces, CinCs, and national agencies would have a share in the spectrum division. This points to an extreme crisis in ability to satisfy requirements set forth in the previously discussed documents. [Ref. 15]

Prior to the Persian Gulf War, multimedia satellite communications did not exist in the Navy. In fact, UHF SATCOM terminals were only available onboard a handful of platforms. At the same time, EHF terminals existed only on an experimental basis. This lack of over-the-horizon communication capability forced many commanders to spend operational funds to obtain an INMARSAT commercial maritime satellite communication capability. [Ref. 20] Commanders began to realize the value of satellite communication to modern joint warfare. As a result, the CNO began a push to install a mix of SHF, EHF, and upgraded UHF terminals, along with an increased commercial capability, to almost every Navy vessel. This rapid influx, however, was accomplished without an overall strategic plan. [Ref. 20]

In recognition of the increased technological capabilities of SATCOM, several attempts to define a coherent architecture were attempted from 1992 through 1996. Each effort reached an independent set of conclusions, but never a DoD wide consensus of opinion. At the time, the UFO and Milstar constellations had yet to be launched, and funding for the services was under fire from Congress. Scheduled decision points were allowed to slip, shortening the development time for a replacement system.

These study efforts have produced many paper reports, and much political fighting among the services, but no approved SATCOM road map for the future. Two major hurdles have prevented a coherent solution from being reached, the enormous complexity of the SATCOM problem, and the fact that costs associated with fielding a new system are expected to exceed $50 billion. [Ref. 4]

The latest effort, dubbed the "Transition Planning Effort," was begun in 1996. Led by the Deputy Undersecretary of Defense for Space (DUSD (Space)), this effort is working to refine a very broad architecture trade space defined by the DoD Office of the Space Architect (OSA). The goal is to provide a road map by December 1997 for building the MILSATCOM system of tomorrow. To make the task more manageable, the effort has been divided into smaller sections, with the Navy being assigned to lead the low data rate effort named the "Mobile Users Study" or MUS. [Ref. 20]

Led by the Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN (RDA)), the Navy has established an Integrated Product Team (IPT) to oversee the MUS effort. Three Working Integrated Product Teams (WIPTs) have been given individual tasking by the MUS IPT. They are the Requirements WIPT, Systems Engineering WIPT, and Acquisition Planning WIPT.

The Requirements WIPT is a joint effort headed by Naval Space Command. Representatives from the four services, the Joint Staff, and the Defense Information Services Agency vote on all decisions, with each agency having an equal vote in a majority rule forum. Additional support is provided by a large array of contractors, the National Reconnaissance Office (NRO), the National Security Agency (NSA), and various government agencies with a stake in the SATCOM planning process. [Ref. 21]

The goal of the Requirements WIPT is to reach a consensus on the requirements for low data rate mobile SATCOM. The group used a top-down approach to requirements definition, basing their decisions on guidance provide by the Joint Chiefs of Staff publication *Joint Vision 2010*, and service specific vision documents such as the Navy's *Forward From the Sea*. These general requirements then translate to specific network requirements, as expressed in the ERDB. This approach enables a direct tie between the granular detail of individual network needs and the warfighting impact of that network if lost. [Ref. 20]

The outcome of the Requirements WIPT process includes three products, a requirements matrix, appropriate requirement definitions, and an assessment of the impact of unsatisfied requirements on warfighting capabilities based upon a computer analysis using the software tool MAST. The process and products are depicted in Figure 3. These products are then fed to the Systems Engineering and Acquisition Planning WIPTs as inputs to their decision cycles. The goal of this entire process is to provide a comprehensive transition and implementation plan for providing mobile LDR service enroute to an objective architecture.

After examining all of the requirement documentation, the Requirements WIPT narrowed their high level requirements down to eight issues. Each voting member then ranked items on the list in accordance with their individual service desires, however, no relative weighting criteria was applied. This means that each requirement carries equal weight in an ordinal ranking. There was no way to delineate if a particular requirement was significantly more or less important than its neighbor. Results are listed in Table 3. [Ref. 21] Definitions for each requirement are tied to terms defined in the CRD. Each

definition is provided with amplification to meet the needs of the MUS. These definitions are included as Appendix B. This data was then presented to the Systems Engineering WIPT to be used for decision making in architectural trades, and for further refinement.

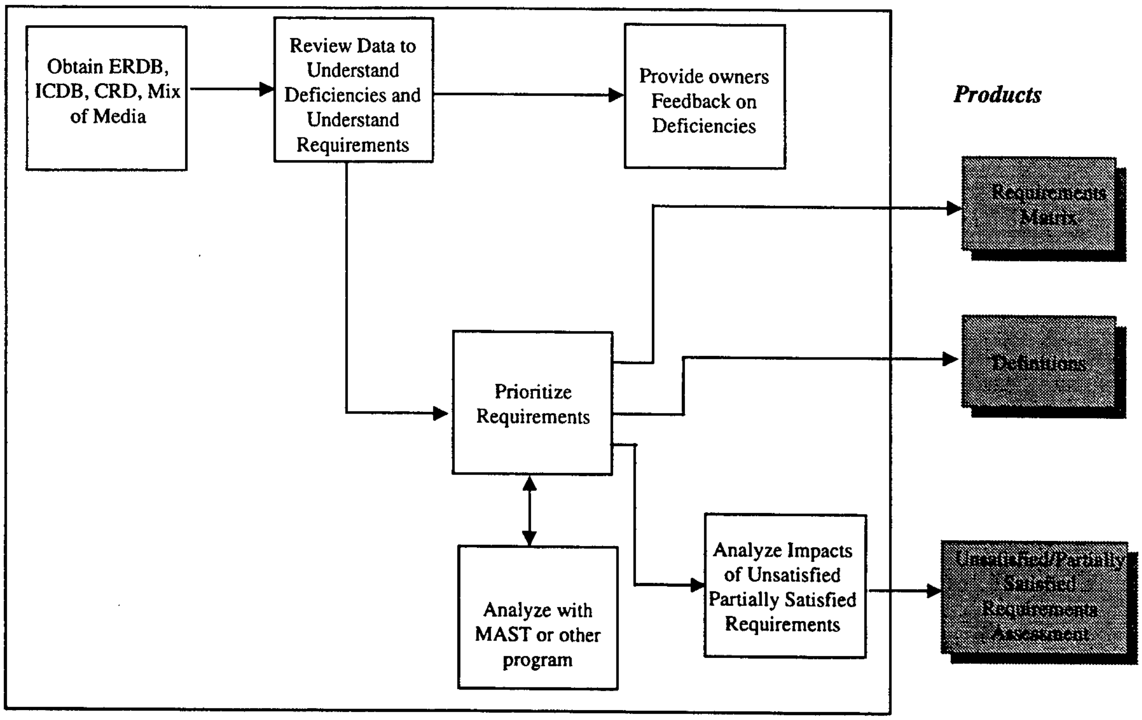

Figure 3 - MUS Requirements WIPT Process and Products [Ref. 21]

The Systems Engineering WIPT has produced version 1.0 of a document expanding upon the requirements presented by the Requirements WIPT. Their intent is to provide industry with a list of more specific design requirements that reflect needs stated in MOP 37 and the ERDB. [Ref. 22] While the Requirements WIPT is comprised of system users, the Systems Engineering WIPT is a gathering of communications engineers from DoD agencies and support contractors. This group has a better understanding of the requirement design process, and is taking an iterative approach to refining the eight stated requirements into verifiable functional and performance requirement statements.

This group recognizes that under the DoD's push to reduce costs by purchasing commercially developed products, many contractors may already have designed systems with the potential to meet the military's needs. Because of this, many items on their expanded requirements list are phrased in terms of questions regarding what type of

service a candidate system can provide. This indicates that many aspects of a future SATCOM system not well understood, or are open to a wide range of performance parameters. This can be seen as an attempt to poll industry on the direction technology is taking, or effort not to constrain the solution the space.

Required Capabilities	Voting Members							
	USA	USN	USAF	USMC	JCS	DISA	**Avg**	**Rank**
Assured Access	1	1	1	2	1	1	**1.17**	**1**
Netted Comms	2	2	2	1	2	2	**1.83**	**2**
Comm on the Move	3	3	6	3	3	4	**3.67**	**3**
Joint Interoperability	4	4	7	5	4	6	**5.00**	**4**
World Wide Coverage	5	5	5	7	6	3	**5.17**	**5**
Point-to-Point Comms	8	6	3	4	5	5	**5.17**	**6**
Broadcast	6	8	4	6	7	8	**6.50**	**7**
Polar	7	7	8	8	8	7	**7.50**	**8**

Table 3 - MUS Requirements Matrix. From Ref. 21

The entire MUS effort is moving forward under a schedule deadline. On-orbit MILSATCOM systems have become coveted resources, but can be very fragile. Once a satellite is in orbit, servicing and repair are not possible using current technology. Present reliability analysis predicts the demise of all current and planned MILSATCOM constellations in the middle of the next decade. In order to provide replacements, programs and funding must begin now. The MUS IPT is working to win JROC approval for their architecture transition plan to include a gapfiller component, an objective architecture, and a plan for next generation terminal population. This must occur in late 1997 in order to enter the future years budgeting process in time to replenish or replace current systems. [Ref. 20]

The MUS effort must be seen as a short fused effort. The deadlines have been known for some time, but the responsible parties have been unable to work together to reach a consensus. This is apparent from the previous studies that had been undertaken, and then allowed to languish. The MUS participants have worked hard to provide a reasonable amount of detail in a short period of time to make up for several years of political and budget battles. Their products represent a reasonable approach to stating an enormous set of requirements in a useable format. However, greater care must be taken

in this requirements generation process to avoid stating requirements in terms of what can be done today. Instead, as much room as possible must be left to industry for developing innovative solutions to a problem that depend on rapidly evolving technology.

III. COMMUNICATION SATELLITE TECHNICAL COSIDERATIONS

Before discussing potential solutions that will satisfy the requirements laid out for a mobile LDR MILSATCOM system, some of the major technical issues need to be addressed. The issues discussed in this chapter are intended to provide a background for understanding potential tradeoffs in designing an objective system. Technological advances in hardware and software will always affect design trades, but the physical principles under which they operate remain constant.

A. FREQUENCY SPECTRUM

One of the most basic decisions to be made when designing a communication system is what channel the information will be sent through. For satellite communications, that channel is the electromagnetic spectrum travelling through the Earth's atmosphere, and through space.

The electromagnetic spectrum can be thought of as energy travelling at the speed of light. This energy oscillates at a continuum of frequencies ranging from a frequency of close to 0 Hz to higher than the terrahertz (10^{12}) range. Terrestrial radio and satellite communication systems mostly use the radio frequency range of this spectrum from 3 MHz to 300 GHz, although some applications are being developed at higher frequencies using laser applications to communicate. Within this range, the ITU has developed standard nomenclature bands on a logarithmic scale, so that each successive band contains ten times the bandwidth of its predecessor. [Ref. 23] The most widely used frequency bands for SATCOM are the UHF (300 MHz – 3 GHz), SHF (3 GHz – 30 GHz), and EHF (30 GHz – 300 GHz), are depicted in Figure 4 by their relative bandwidth size. Frequencies below UHF exhibit an increasing tendency to be trapped within the earth's ionosphere and are used for terrestrial long distance, beyond line-of-sight, communications purposes.

Figure 4 - RF Frequency Bands

All three of these bands are limited to line-of-sight communications, but interact differently with atmospheric phenomena and physical obstacles. Because of this, their applications vary. Also, within each band, sub-bands have been identified for satellite communications purposes, and given unique letter designators. These bands have been reserved for general applications by international agreement. It is extremely unlikely that the military will be able to obtain any new frequency assignments for MILSATCOM purposes. Table 4 depicts currently assigned bands and their characteristics. [Ref. 24]

Letter Designator	ITU Band	Frequency Range (GHz)	Bandwidth (MHz)	USE
L	UHF	0.39-1.6	50	Commercial, Military
S	UHF/SHF	1.65-5.2	90	Tracking, Telemetry, and Control
C	SHF	3.9-6.2	500	Commercial
X	SHF	5.2-10.9	500	Military
Ku	SHF	10.9-17.25	500	Commercial
Ka	SHF	17.5-30	2500	Commercial
			1000	Military
Q	EHF	36-46	2500	Military
V	EHF	46-56	-----	
W	EHF	56-100	-----	

Table 4 - Satellite Frequency Band Designations and Characteristics. From Ref. 24

In addition to their line-of-sight propagation, these bands have a few other common characteristics. First of all, as previously stated, all electromagnetic waves travel at the speed of light. This means that information using a radio channel will travel from transmitter to receiver at the same speed regardless of frequency. Longer distances mean longer delay. In terrestrial line-of-sight networks the delay will be insignificant, but when geosynchronous satellite communications systems are used, the round trip will take approximately one quarter second plus any processing time involved. This can be a significant delay for voice applications. Although information data rate requirements are fundamentally independent of transmission channel frequency, it is important to recognize that operations such as error detection and correction, addressing, supervision,

synchronization, and spectrum spreading increase the required channel bandwidth, which is a scarce commodity in the lower frequency bands.

Despite certain similarities, each radio frequency (RF) band possesses distinctive features that determine suitability for different applications. Understanding these differences is the key to recognizing the potential tradeoffs among the different bands for satellite use.

According to the ITU definition, the UHF band ranges from 300 - 3000 MHz [Ref.24], although military definitions refer to frequencies as low as 225 MHz. It is primarily a line-of-sight signal used by the military for air-to-air and air-to-ground communications. These systems are good for hand-held applications due to a relatively low power requirement and the ability to use dipole, or whip antennas, which are nearly omni-directional and require very little pointing accuracy. This band can easily operate at data rates of 2.4 kbps and higher, but is susceptible to jamming and interception due to its widespread usage and nearly omni-directional antenna pattern.

The SHF band covers the spectrum from 3 - 30 GHz. It is widely used for terrestrial based line-of-sight, high data rate, microwave links. [Ref. 24] Current MILSATCOM use of this band is for high data rate applications due to the relatively large bandwidth availability compared to UHF. For the same size antenna, wave characteristics in this region allow more directional transmission than the UHF band. This results in a narrower beamwidth, reducing the probability of both jamming and signal interception. Spread spectrum techniques can be used to reduce this possibility even further. Modern systems use antennas that are too large for most mobile applications, other than ships. Most are transportable rather than mobile, and are towed by trucks to an installation location where they are set up for stationary use.

EHF use is still very new to the military. Utilizing spectrum from 30 - 300 GHz, this band possesses a wealth of untapped capacity. Due to its short wavelength, EHF can be used with very small aperture dish antennas and very narrow beamwidths. The low probability of intercept (LPI) and jamming are very favorable. The problem with EHF is high attenuation due to rain and atmospheric attenuation and scattering. High humidity can cause signal losses of several dB, while heavy rain can cause over 30 dB of signal loss to EHF frequencies. [Ref. 25] Large platforms such as ships and ground stations may be able to produce enough transmitted power to overcome this, but few small platforms will be able to do so. Additionally, satellite transmitters are limited in power production and output, so terrestrial receivers require sufficient gain margin in their

equipment to overcome this obstacle in order to satisfy availability criteria. Shadowing, or signal loss due to obstacles, increases with frequency. Little work has been done to test these high frequencies in constrained environments such as urban and jungle locales. It is believed at this time that EHF frequencies would require a direct, or nearly direct, line-of-sight between transmitter and receiver. [Ref. 25]

The amount of bandwidth required for a transmission channel depends upon processing requirements and modulation scheme. A digital signal contains two basic types of information, intelligence bits and overhead bits. Intelligence is the user's data, voice, or video information being transmitted to the receiver. Overhead includes bits added to the signal for purposes of error detection and correction, routing and addressing, encryption, and any direct sequence spread spectrum encoding. Often, only a small percentage of signal bandwidth is used for intelligence bits.

It is important to once again note that frequency spectrum is assigned by international agreement. The International Telecommunications Union (ITU), an arm of the United Nations, is responsible for setting international communications policy and standards. Their decisions are enforceable under international law. Just because the United States military has a block of frequencies available for use within its borders, does not mean that those same frequencies will be available in foreign lands or international waters. Planning is needed to deconflict frequency assignments when operating in these areas, or any communications system could be rendered completely ineffective either by law or through interference and nuisance jamming.

Spectrum availability is also under attack from within the United States as well. Elements of both the Legislative and Executive branches have made repeated proposals to sell military spectrum allocation to the commercial market in an attempt to raise money. In the author's opinion, this is a shortsighted effort to profit at the expense of the military's most flexible spectrum allocation that could prove to be very costly in the end. The government may be forced to spend large amounts of money to lease back frequency rights from commercial entities, as well as the equipment needed to operate with them. So far these efforts have not succeeded, but have not gone away.

B. HARDWARE

In the past it has been customary to design terminals around a satellite's capabilities. This has led to terminals that were cumbersome to use, could not be fielded

in a timely manner, and provided little added value to many mission areas. It has been shown that the radio segment of a MILSATCOM system is responsible for most of the system lifecycle cost. Additionally, due to the relatively short life spans of satellite constellations, the terminals are not completely fielded until the constellation has aged beyond a significant portion of its useful life. [Ref. 26]

Next generation SATCOM constellation designers must learn the lessons of the past. The current pace of technology growth will not allow the same plan to be followed. Instead, satellite constellations must be designed to work with particular terminal characteristics. The entire system needs to be viewed from the perspective of the disadvantaged user. Terminal capability limitations will determine the level of service to be provided by the space based assets.

Mobile manpack or handheld terminals are largely constrained by size and weight. The two physical components having the largest effect on these parameters are the power source and the antenna. These two items must be designed to provide optimum capabilities within the size and weight requirements defined by the user. These considerations also affect other mobile platforms, but to a lesser extent. If a system can be designed to meet the needs of the more restrictive terminals, it can be adapted for the less constrained case, and ideally provide greater service.

1. Terminal Power Sources

Electrical power for man portable terminal operation comes from a storage device or battery. Batteries come in a wide variety of sizes and shapes due to their power requirements and chemical composition. Terminal output must meet Occupational Safety and Health Standards for exposure set by the United States Government. Within these limits, batteries are designed to meet characteristics such as discharge time, recharge cycles, human and environmental safety, and energy density (watt-hours/kilogram). [Ref.27]

A comparison of commonly available battery types is provided in Table 5. This table demonstrates the types of trades that must be considered when designing small handheld or manpack terminals. [Ref. 25] Power output is paramount, but this must be balanced by considerations such as cycle life, weight, and life-cycle cost. There is seldom an obvious solution, but the design must be compatible with operational concepts in order to be of value to the user.

	NiCd	NiMH	SLA	Li-ion	Solid Li-Polymer	Reusable Alkaline
Energy Density (W/kg)	30-60	60-80	25-30	100-130	70-200	80
Cycle Life (capacity decrease to 80%)	500-1500	500-800	200-500	500-1000	100-150	10
Fast Charge Time (hrs)	1.5	2-4	8-16	3-4	8-15	2-3
Overcharge Tolerance	moderate	low	high	very low	N/A	moderate
Self-discharge per Month	10-20%	30%	6%	10%	5-20%	0.3%
Operating Temp (^{0}C)	-40 to +60	-20 to +60	-20 to +60	-20 to +60	N/A	0 to +65
Maintenance Requirement (for max service life)	30 days	90 days	3-6 months	N/A	N/A	N/A
Typical Battery Cost	\$50 (7.5V)	\$70 (7.5V)	\$25 (6V)	\$100 (7.2V)	\$90 (8.1V)	\$5 (9V)
Cycle Cost	\$0.04	\$0.14	\$0.10	\$0.10-\$0.20	\$0.60	\$0.50
In Commercial Use Since	1950	1990	1970	1991	N/A	1992

Table 5 - Portable Terminal Typical Battery Comparison Chart. After Ref. 25

Larger terminals such as those on aircraft and ships can generally rely upon their platform's power generation capacity, but space based assets are unique. They must provide power via a combination of solar cells and storage devices. Solar cells must be arranged to receive a maximum amount of solar energy. Because of their relative motion with the Sun and the Earth, satellites will experience periods of blackout. Additionally, these components will degrade over the life of the satellite and provide less power. Because of this, satellites are also constrained in the amount of power they can produce, but are not limited by the same electromagnetic radiation exposure restrictions that many terminal transmitters are. Designers must balance the capabilities and constraints of each node of the system in order to take advantage of the characteristics of each.

2. Antennas

Antennas are large drivers of system weight and size. The ideal antenna radiates equal power in all directions, but this is a theoretical limit. Commonly used dipole or whip antennas are normally considered omni-directional, but actual radiation patterns depend upon nearby ground structures, ground plane, and bandwidth. Many design variations have been used to overcome this limit in order to reduce blind spots in the pattern, but true omni-directional radiation is difficult to achieve.

Energy radiated from an ideal isotropic antenna spreads in a spherical pattern away from its source. Because of this, the amount of energy arriving at a receiving antenna is reduced in proportion to the square of the distance from the transmitter. Each antenna has a gain associated with it. Gain is a function of antenna efficiency, effective aperture area, and transmitted or received frequency. It is usually expressed in decibels, and is a measure of an antenna's ability to concentrate its radiated energy. Equation 1 is the equation for antenna maximum directive gain. [Ref. 27]

$$G = \eta \left(\frac{\pi d f}{c} \right)^2$$

Equation 1 - Antenna Gain

Antenna efficiency, η, is the reduction in radiated or received power due to factors such as feed loss. Typical efficiencies range from 50 - 70 % [Ref. 27]. A higher efficiency equates to higher radiated power. Effective area in this equation is based on the diameter, **d**, of a parabolic dish. Gain increases with the square of the antenna aperture diameter, and the square of the signal frequency, **f**. The factor **c** is a constant representing the speed of light.

As Equation 1 shows, there is room for significant tradeoffs in antenna design. Exposure limits will continue to constrain emissions, but how those emissions are used can be subject to much creativity. Most satellite communication systems use a familiar parabolic dish antenna to concentrate radiated energy into a usable quantity. However, dish size is dependent upon wavelength, and frequencies in the UHF band would require huge dish sizes to maintain a consistent beam pattern. Because of this, UHF systems, especially for mobile applications, require the use of some form of dipole antenna. EHF systems on the other hand are able to make use of small dish antennas. In fact, EHF antennas developed for submarine applications are only a few inches in diameter.

Another issue with parabolic dish antennas is pointing accuracy. The narrower the transmitted beam is, the more accurately it must be pointed it the intended recipient. This introduces further complexity into the system, as well as increased weight and size. Ships at sea have been able to overcome this problem, usually with the use of multiple antennas to prevent superstructure masking, and gimbaled mounts to remove ship motion.

More mobile platforms such as aircraft, motor vehicles, and foot soldiers generally lack the ability to add dish antennas with automatic tracking devices, so lower frequency omni-directional antennas are preferred.

A potential solution to the pointing problem at higher frequencies is the use of phased array antennas. These consist of a set of small fixed elements that work to electronically steer a signal by applying differential transmission characteristics to individual transmission elements. Since beam steering is accomplished without moving a large dish, tracking can be done much faster, and without a large gimbaled dish. [Ref. 28] Phased arrays are not in widespread use because they have been traditionally expensive and very bulky, but technology is changing.

Several companies have developed small and inexpensive phased array elements that are still being tested. Their target market is the home satellite reception market, with the goal of bringing production costs down from thousands of dollars per element, to fewer than twenty dollars. Tests have already been run in conjunction with the Air Force by using conformal phased arrays on an aircraft fuselage to provide satellite communications. Further tests are currently being run with the Army to employ a flat plate antenna with approximately a dozen dime sized phased array elements, to communicate in the SHF band with orbiting Unmanned Aerial Vehicles (UAVs). Their prototype is man portable with a 1 millisecond scanning beam to maintain pointing accuracy with a receiver. [Ref. 28] Additionally, the Navy is working to develop conformal phased array antennas for shipboard use, where antenna space is at a premium.

Although the communications applications of phased arrays can still be considered developmental, they should be given serious attention. As costs and size come down they become more attractive and affordable for a wide variety of applications. They may be able to overcome many of the limitations of dish antennas while allowing access to the capabilities available in higher frequency bands.

C. ORBITOLOGY ISSUES

Much of a satellite constellation's capability is determined by its orbit. All Earth orbiting satellites are contained in a plane passing through the center of the Earth. Different orbits are distinguished by their altitude and inclination (as determined by the angle between the orbit plane and the Earth's equator). These factors affect parameters important to communication satellites such as period, access area, and coverage area.

A satellite's period is the amount of time required to complete a single orbit of the Earth. Basically, the higher the orbit the longer the period. The shortest period occurring at the lowest orbital altitude is about ninety minutes.

Access area is a description of the area of the Earth that is visible to a satellite. It is independent of satellite hardware capabilities, and proportional to altitude above the Earth. Even at an infinite distance from the Earth, access area cannot exceed half of the Earth's surface.

Coverage area is a subset of access area. It is that portion of the access area that a satellite's sensor can actually see. Most satellites are unable to cover their entire access area at a single instant in time. For a communications satellite, coverage is based on the antenna gain pattern, and the amount of area it can service at one instant.

Most communication satellite orbits are circular or nearly circular in order to maintain steady gain patterns. Once a satellite is placed in orbit, the cost to change that orbit, in terms of both fuel and operational flexibility, is very high. To change an orbit inclination by as little as 10° requires an expenditure between 18% and 35% of the spacecraft's total weight in fuel, depending upon fuel type and orbit altitude. Launch vehicle size and lift capacity limit the amount of fuel that a satellite can carry. More fuel means a reduced weight allowance for mission hardware. Once a plane change is made, it is unlikely that the fuel capacity will exist for another. Additionally, less fuel will be available for routine stationkeeping purposes that will reduce useful satellite mission life.

Most orbits can be divided into general descriptive categories based upon their altitude and orbit eccentricity. These categories are detailed below.

1. Low Earth Orbits

Low Earth orbits (LEO) start as low as 300 km above the Earth's surface. Although this is generally considered to be above the atmosphere, its effects are still felt in the form of aerodynamic drag on the satellite, and frequent station keeping maneuvers must be executed to prevent atmospheric capture. These maneuvers are performed by thrusters burning a portion of the spacecraft's fuel supply that will eventually be exhausted. LEO orbits are generally defined to include altitudes up to 1000 km. The upper boundary altitude is determined primarily by the need to remain below the harmful radiation effects of the Van Allen belts. LEO orbital periods range from 90 to about 100 minutes. [Ref.27]

Due to their close proximity to the surface of the Earth, satellites in LEO orbits have relatively small access and coverage areas. This means that to provide continuous coverage of the Earth, many satellites are needed in highly inclined orbits in order to reach the extreme latitudes. The result will be increased costs and complexity due to the high numbers of satellites required both to populate the constellation, as well as replenish it. Commercial LEO satellite constellations planned for the near future are designed to contain anywhere from a few spacecraft to several hundred.

Additionally, a high relative motion is created between the satellite and the ground based transceiver on the order of 7.5 km/s [Ref. 27]. This leads to a much higher doppler shift than most currently fielded radios are equipped to handle, and represents a design challenge. Also, due to its low altitude and fast motion, a communication satellite will likely disappear below the radio horizon before communications are complete, necessitating overlapping coverage areas and effective signal handoff mechanisms between satellites within a constellation. Finally, if system antennas require strict pointing accuracies in order to maintain the communications link, the high relative motion will make this task difficult.

In their favor, LEO communication constellations require much less received signal power to operate. This works to the benefit of the disadvantaged user who must operate with small manpack or hand-held, battery operated, terminals. Antenna pointing accuracy requirements are reduced due to their relative proximity, and small omni-directional antennas may be used.

Another benefit is wider frequency reuse. Due to smaller coverage areas, or footprints, the same frequency can be utilized by a variety of users in different geographical regions without interference. This requires proactive constellation management to divide the total coverage area into many cells using non-overlapping frequencies, but may prove valuable in an age of shrinking military spectrum assignments and increased communication requirements.

2. Medium Earth Orbits

Medium Earth orbits (MEO) start above 1000 km and extend out to geosynchronous altitudes. Because of their higher altitudes, access areas, coverage areas, and periods are generally larger than LEO orbits. In fact, periods range from 100 minutes

up to almost 24 hours. Most MEO based satellites reside in a 12-hour orbit period at about 20,000 km above the Earth's surface.

At these altitudes, MEO satellites are subjected to the intense radiation fields of the Van Allen Belts. These solar particles trapped in the Earth's gravitational and magnetic fields have detrimental effects on spacecraft longevity. In particular, they accelerate solar panel degradation, upset electronic logic sequences, and cause premature electrical component burnout. Satellites built to exist in this environment must be hardened to withstand these effects at significantly increased costs. [Ref. 27]

At higher altitudes, a communication satellite constellation would require fewer spacecraft to populate. This means fewer to build, fewer launches, and fewer spares. This can be a large cost reduction factor. The current Navstar/GPS constellation operates with 24 satellites in 12-hour orbits [Ref. 29]. This number guarantees that at least four are in view at all times. Communication constellations may not require these numbers to assure coverage.

As MEO satellites move farther from the Earth, required transmitter power increases as previously discussed. This increases the burden on the Earth-based terminal to provide a higher power output. Another advantage is reduced doppler shift as well as reduced pointing accuracy problems, due to the slower relative motion between terminal and satellite when compared to LEO orbits.

Finally, as the MEO satellite's coverage area grows, frequency reuse capability diminishes. This reduces some of the constellation management requirements, but also reduces spectrum available to the user.

3. Geosynchronous Orbits

Geosynchronous orbits (GEO) are distinguished by their 24-hour orbital period. This places them at an altitude of 35,786 km above the Earth. [Ref. 27] Most GEO satellites have a near zero inclination to allow them to stay over a relatively constant geographical point along the Earth's equator. Small orbit perturbations prevent them from achieving a true geostationary orbit over a single spot at all times.

Most of today's communications satellites are in GEO orbits. This allows receivers at fixed geographical locations to maintain pointing accuracy in a fixed direction. Present mobile receivers are at a disadvantage. They must use mechanical

tracking devices, multiple antennas, or stop and set up a dish antenna to establish a temporary communication link.

The access area from GEO altitude is roughly one third of the earth's surface. This means that most of the globe can be accessed with as few as three spacecraft. However, because they are located over the equator, polar regions are not covered. In fact, some outposts near the polar circles are able to achieve only intermittent communication links when slightly inclined GEO satellites reach the limits of their inclination.

RF power requirements are also an issue with GEO constellations. They are located 40 to 100 times farther from the Earth's surface than LEO satellites. This means that as little as one ten-thousandth of the power that reaches a LEO spacecraft will reach a GEO spacecraft. Ground transmitters must produce significantly higher signal strength in order to reach a GEO communications satellite with the same gain as a LEO craft. Doppler shift considerations, however, are minimized.

Frequency reuse is most severely restricted at GEO altitudes. When only three or four regions of the Earth are covered, the available spectrum must be used very efficiently. This can be accomplished through multiplexing schemes and priority assignments.

4. Highly Elliptical Orbits

Most communication satellite orbits are nearly circular, however, highly elliptical orbits (HEO) are sometimes used. Their advantage is a relatively long dwell time during most of their orbit period in order to give GEO-like capabilities to areas inaccessible to GEO satellites. The most commonly used HEO is called a Molniya orbit.

The Molniya orbit was developed by the Soviets for their communications satellites. Due to their extreme northern latitudes, many of their satellite communication users were unable to access satellites in GEO orbits. It is characterized by a 12-hour period, an apogee at LEO altitudes, and a perigee past GEO at about 40,000 km. Additionally, it has an inclination of 63.4° to keep apogee in the Northern Hemisphere and maintain high latitude coverage. [Ref. 27] Two satellites placed out of phase in this orbit will provide continuous polar coverage.

HEO orbit based satellites not only experience relative motion, but it is a constantly changing motion. This presents challenges for both antenna pointing and

doppler shift. Power output of a terrestrial based transmitter must be sufficient to reach GEO altitudes. Also, due to its limited coverage area, frequency reuse will be difficult to achieve. Despite their disadvantages, Molniya orbits are the easiest method for providing polar coverage with the fewest spacecraft.

D. LINK BUDGET

Much like terrestrial radio links, satellite links depend on a certain minimum amount of transmitted signal power reaching the receiver. If that minimum signal strength is not achieved at the receiver, then the signal is lost. Once a signal is transmitted, it will continually degrade along the path to the receiver. System designers must account for each element that causes loss of signal strength, and budget to provide the proper balance between transmitter and receiver design characteristics. This balance is known as a link budget.

The link budget is based on the link equation, which relates parameters needed to derive the signal to noise ratio of a communication system. A common form of the link equation is [Ref. 27]:

$$P_r = \frac{P_t G_t G_r}{L_s}$$

Equation 2 - The Link Equation

In this equation, P_r represents the power at the receiver, P_t is the transmitted power, and G_t and G_r are the respective transmitter and receiver antenna gains. L_s designates "free space loss". This represents the fact the transmitted signal spreads spherically from the transmitting antenna, so energy loss is proportional to the square of the distance from that antenna. This free space loss is also proportional to the square of the frequency, so higher frequencies experience higher free space loss. Since each gain term is proportional to the square of the frequency, the net result is that received power varies directly with the square of the frequency, and inversely with the square of the distance between the transmitter and receiver.

The above link equation is a theoretical expression of received power. Other losses occur due to hardware, such as line losses between antennas and amplifiers, as well as losses due to atmospheric conditions, especially moisture content [Ref. 6]. These

losses can lead to a significant reduction in power available at the receiver, which must be accounted for.

To provide for effective link planning, a link budget is constructed in tabular format. Since satellites are used as nodes and not terminals, two links must be taken into account, an uplink and a downlink. Table 6 depicts a typical ship-to-shore SATCOM link via the commercial satellite communication system INMARSAT (International Maritime Satellite) [Ref. 23]. This link budget contains margins in both uplink and downlink to account for atmospheric perturbations and system operation parameter changes. Systems operating in a higher frequency would have to include larger margins to account for rain or other factors.

The final term in both the uplink and downlink sections is C/N_0, or the received signal power to noise ratio, also known as the signal to noise ratio (SNR). This figure must be large enough to allow the receiver to detect the transmitted signal in the presence of competing noise. In the final section, these figures are combined to realize an overall E_b/N_0, or the bit energy to noise power density ratio. This ratio is used to predict the bit error rate achieved in the system, an overall measure of performance in a digital system. Typical bit error rates are on the order of 10^{-4} or 10^{-5}. The k term is Boltzmann's constant, used in the calculation of thermal noise in the receiver.

UPLINK		
Ship Terminal EIRP	26.0	dBW
Free Space Loss	188.31	dB
Margin	5.0	dB
k	-228.6	dBW/K/Hz
Satellite G_R/T	-17.0	dB/K
Satellite Receiver Gain	6.0	dB
C/N_0	50.29	dBHz

DOWNLINK		
EIRP	18.0	dBW
Free Space Loss	196.2	dB
Margin	5.0	dB
k	-228.6	dBW/K/Hz
Shore Terminal G_R/T	32.0	dB/K
C/N_0	77.4	dBHz

COMBINED		
Total C/No (Up and Down)	50.3	dBHz
Bandwidth	33.8	dBHz
E_b/N_0 (achieved)	16.5	dB
E_b/N_0 (required)	9.5	dB
Additional Margin	7.0	dB

Table 6 - Typical Ship-to-Shore Link Budget via INMARSAT. After Ref. 23

When designing a satellite communication system, close attention must be paid to the link budget. All of the technological issues discussed in this chapter affect this budget. Tradeoffs in operating frequency and hardware must combine to produce enough power at the receiver to meet the link requirements and provide enough margin to account for unknowns in the operating environment. This is especially challenging when designing to meet the needs of the most disadvantaged user, the small portable or hand held terminal operator.

E. SATELLITE ISSUES

The satellites themselves present many limitations on the system regardless of their mission. Failures, susceptibility to outside influences, and security can all present problems. Part of defining a new system must consider the potential outcomes of these scenarios when developing the system design and the operational concept.

Launch success rates are generally high, but failures do occur. These failures range from catastrophic failure at the launch site or in flight, to separation problems or inability to reach proper orbit in flight. Costs for these failures are not just in terms of dollars lost, but also in terms of operational capability sacrificed before another unit can be launched in its place.

Unlike most pieces of hardware, an orbiting satellite can not undergo routine maintenance or repair. Each component must be carefully constructed and integrated before being thoroughly tested prior to launch. Once it leaves the launch pad there is not much that can be done in the event of a satellite failure. Often, software and hardware combinations can be used to command configuration changes in flight, but these are usually limited. Many systems have built in redundancy in case of a failure, but these add weight, cost, and size to the vehicle.

Once operating in its orbit, a whole host of outside influences can affect satellite operation. The natural environment can impose a harsh operating regime on the satellite via exposure to damaging radiation particles, as well as rapidly fluctuating temperature extremes. Debris, either natural or man-made, can pose significant collision risks. Two objects approaching each other head-on at LEO altitudes can have a closure speed exceeding 14 km/s!

Additional threats are possible from ground-based sources. These include anti-satellite (ASAT) attacks and jamming attacks from enemy forces. With so many groups

having access to nuclear weapons, and launch facilities available on the open market, it would be easy for a hostile force to explode a nuclear weapon in space that could effectively shut down or destroy satellite communications capability.

Over-the-air communications travel through open space. This means that signals are susceptible to detection and interception. Methods such as signal encoding, spectrum spreading, and the application of narrow-beam signals help to reduce this threat, but it still exists.

Finally, one of the weakest nodes to exploit in order to disrupt satellite communications is the ground station. The ground station can be responsible for monitoring the health and activity of the satellites in a constellation, as well as controlling the flow of information over a SATCOM network. Many satellite systems operate from a single ground-site location that can be easily accessed by an intruder. Depending on the level of security, and the desired effect on the satellite, a hostile force could attempt to destroy the ground station antenna or control facility. This can be avoided through the implementation of adequate security measures, the dispersal of control nodes, and the application of crosslinking capability on the satellite that reduces the need for ground station interference.

No system can be built foolproof, but vulnerabilities need to be recognized and planned for. Identified vulnerabilities need to be matched with the probability and the consequences of such an event occurring. Safety and security measures can then be built around the perceived level of acceptable risk. If risks prove unacceptable, then an alternative course of action will be necessary.

IV. SPACE COMMUNICATIONS SYSTEMS 2000

When attempting to satisfy a new set of requirements, strong attention must be paid to the potential lifecycle costs of any proposed solutions. One of the most inexpensive ways to satisfy new requirements is through the use or modification of an existing system. This can also serve to present insight into further design requirements where backward compatibility is an issue.

The military has used satellite communications assets for many years, but only in the last few years has widespread use become important. Technology has matured enough to allow usable data rate channels to be available world wide, and the proliferation of data networks and wireless commercial communications has resulted in a marked reduction in cost. Industry is leading the charge to build bigger, better, and faster SATCOM systems, and the military is in a position to take advantage of this situation. Before setting specifications for future systems, the current inventory and capabilities must be understood.

Today's various MILSATCOM systems were designed and fielded independently to meet a variety of validated requirements. A mix of commercial and military operated systems are in use, almost exclusively from geosynchronous orbits (Some use is made of HEO orbits to provide coverage of the northern latitudes). UHF, SHF, and EHF applications are made with a variety of characteristics for protection. The three major MILSATCOM constellations that will be in use at the turn of the century are the UHF Follow-On (UFO), the Defense Satellite Communication System (DSCS), and the Military Strategic Satellite Relay (Milstar).

A. UHF FOLLOW-ON (UFO)

The UFO MILSATCOM system is being fielded as a replacement for the Fleet Satellite Communication (FLTSATCOM) system and its commercial adjuncts that provided UHF service primarily to the Navy and the Air Force for the past decade. When fully populated, the UFO constellation will consist of four pairs of satellites plus one spare in geosynchronous orbits. Satellites two through seven are currently operational. Their coverage areas are depicted in Figure 5. The first launch failed to achieve a proper orbit and is not part of the operating constellation. [Ref. 24]

The UFO Constellation is designed to provide long haul UHF communications capability to deployed forces. Each satellite has a design life of 14 years, and incorporates a mix of 25 kHz and 5 kHz bandwidth channels with varying output power. Table 7 contains a description of the different UHF channel types and their characteristics. SHF is used to provide a narrow beam, jam resistant, uplink for a Fleet Broadcast downlink. [Ref. 23]

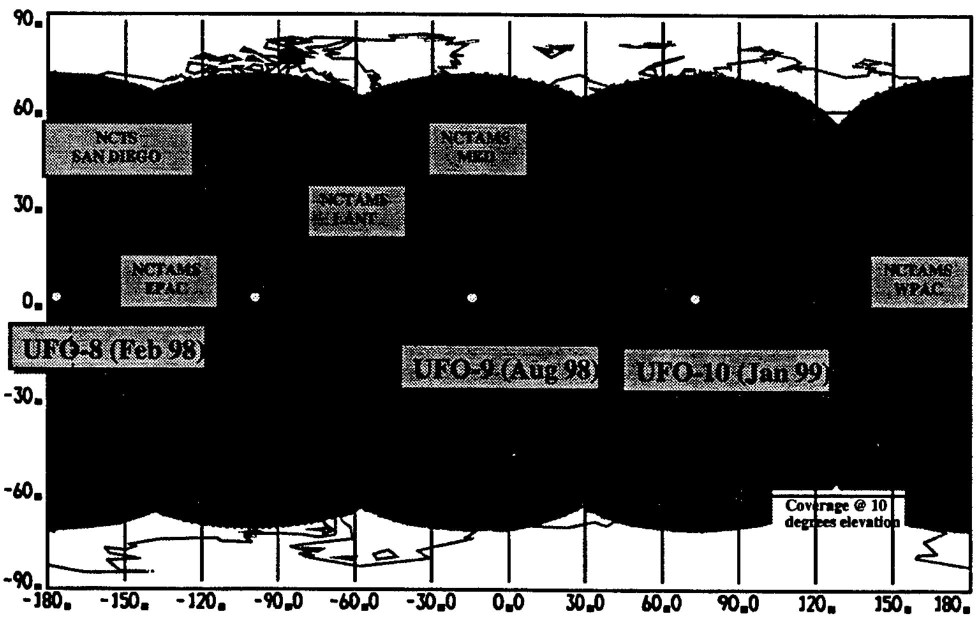

Figure 5 - UFO Constellation Coverage Area [Ref. 24]

Prior to the launch of the first UFO satellites it was recognized that channel and data throughput requirements were growing at a much faster rate than constellation capacity. To increase efficient use of capacity in an attempt to satisfy as many requirements as possible a time sharing scheme called Demand Assigned Multiple Access (DAMA) has been implemented. DAMA allows multiple users to utilize the same channel for information transmission simultaneously.

In a channel using DAMA, a data stream is divided into time frames, each frame is 1.386 seconds in length on a 25 kHz bandwidth channel. Each frame is further subdivided into data time slots and channel control slots. The number of data time slots available varies with data rate and electromagnetic interference. Users with a validated communication requirement request access to a channel and are assigned a transmission time slot based upon their priority, slot availability, data rate, and session duration. Using this scheme, a single 25 kHz channel can accommodate up to 25 users at a time

transmitting in discrete time slots. The 5 kHz bandwidth channel can accommodate data rates up to 2.4 kbps, while the 25 kHz channel time slots can accommodate data rates up to 16 kbps. [Ref. 30]

The DAMA system is still being implemented in many terminals, but so far has been very successful. It is in effect much like picking up a telephone. Each user has a preassigned address, but each address spends much of its time in a standby mode. Such a multiple access scheme reduces idle capacity when other users desire access. It does however involve active system administration for requirement validation and priority assignment. Once this is done, time slot assignment is an automated process carried out by system controllers, and transparent to the user.

Group	Channel Characteristics
I	• Two 25 kHz bandwidth channels • EIRP of 28 dBW • Jam resistant SHF uplink • Four downlink frequencies per channel: 250.350, 250.250, 250.550, and 250.650 MHz
II	• Nine 25 kHz bandwidth channels • EIRP of: Four Channels - 28 dBW Five Channels - 26 dBW • Four downlink frequencies per channel: 251.400 - 269.950 MHz • Four uplink frequencies per channel: 292.850 - 310.950 MHz
III	• Eight 25 kHz bandwidth channels • EIRP of 26 dBW • Four downlink frequencies per channel: 260.375 - 263.925 MHz • Four uplink frequencies per channel: 293.975 - 297.525 MHz
IV	• Eight 5 kHz bandwidth channels • EIRP of 20 dBW • Four downlink frequencies per channel: 243.925 - 244.225 MHz • Four uplink frequencies per channel: 317.015 - 317.325 MHz
V	• Thirteen 5 kHz bandwidth channels • EIRP of 20 dBW • Four downlink frequencies per channel: 248.845 - 249.355 MHz • Four uplink frequencies per channel: 302.445 - 302.955 MHz

Table 7 - UFO Communication Channel Characteristics. After Ref. 23

The UFO constellation contains two other unique features. The first is a Global Broadcast System (GBS) which is being added to the final three UFO satellites. This is a high data rate theater broadcast system for tactical information. The second is an EHF communications package. [Ref. 31]

The UFO EHF package (UFO/E) is a follow-on to the military's first EHF package launched on the FLTSATCOM constellation. The new system is designed as a precursor to the new Milstar EHF SATCOM system. It is designed to receive uplink signals in the EHF frequency range, and downlink them in the UHF, SHF, or both bands, a process known as crossbanding. The UFO/E functions and frequencies are a subset of Milstar capabilities, which will be discussed later. [Ref. 32]

EHF capability will be present on the final seven UFO satellites. Each satellite will have two EHF antennas, a wide-area Earth coverage antenna to cover the entire access area, and a spot beam with a 5^0 aperture. The system will provide LDR data rates up to 2400 bps, and a single channel at 4800 or 9600 bps for a High Speed Fleet Broadcast UHF downlink. [Ref. 33]

This portion of the frequency spectrum is used to provide a jam resistant, low probability of intercept (LPI) signal. This is accomplished due to its narrow beamwidth and use of frequency hopping. By rapidly jumping from frequency to frequency within the available bandwidth in a predetermined pseudorandom sequence, the signal can statistically avoid attempts to be jammed by a narrow beam, focused energy source.

B. DEFENSE SATELLITE COMMUNICATION SYSTEM (DSCS)

The Defense Satellite Communications Satellite (DSCS) has been in operation for more than 25 years, and is now entering its third generation. DSCS is also a geosynchronous constellation with Earth coverage similar to UFO. The first DSCS II satellite was launched in 1971, and those still in use are reaching the end of their useful life. DSCS III satellites have been launched as replacements. Current constellation composition includes a mix of DSCS II and DSCS III satellites with eight active and three in a residual status. [Ref. 31]

The DSCS constellation is designed to provide wideband SATCOM capability to all services using the SHF X-band portion of the frequency spectrum. Due to bandwidth availability in this region, DSCS can support data rates from 75 bps to 1.544 Mbps. As previously discussed, this frequency range also offers the benefits of reduced susceptibility to jamming, as well as LPI protection due to its narrower beamwidth when compared to UHF systems. Additionally, SHF offers more reliable propagation through environmental phenomena than EHF systems, but generally must rely on larger dish antennas at terminal sites. Finally, to enhance its jamming resistance, DSCS III antennas

incorporate a beam forming capability to effectively null reception in directions where signal jamming is detected. [Ref. 24]

DSCS II satellites carried a four channel capability. These channels were split between Earth coverage and spot beam antennas. The DSCS III satellites make use of eight separate antennas and six transponders. Two of the antennas provide Earth coverage, and are connected to two dedicated transponders. A third antenna, known as a multibeam receiving antenna (MBA), is capable of controlling the amplitude and phases of 61 individual beams to selectively produce a desired gain pattern. Two smaller MBAs control 19 beam signals, and the final antenna is a gimbaled dish that provides a 3° spot beam. [Ref. 23]

DSCS III's six channels vary in size from 50 to 85 MHz of bandwidth with 10 to 40 watts of RF power output [Ref. 31]. These channels can be divided further to permit more mobile users to communicate simultaneously through the use of a frequency division multiplex (FDM) scheme [Ref. 23]. This divides each channel into smaller bandwidth allotments that are assigned to separate users. The UFO DAMA scheme permitted each user to use the entire channel for a limited time frame, while FDM allows each user to make use of part of the channel for the entire time.

Naval forces make use of full-duplex SHF communication pathways primarily for command and control ships as well as larger combatants such as aircraft carriers and amphibious ships. The Global Command and Control System (GCCS) and other information networks use DSCS for its wideband capability. Spread spectrum modems can be used to provide further protection from jamming, but Naval force applications emphasize throughput over protection in SHF circuits. [Ref. 32]

C. MILITARY STRATEGIC SATELLITE RELAY (MILSTAR)

The Milstar constellation is the military's newest MILSATCOM system. It is designed to provide secure, survivable EHF communications to satisfy DoD and national requirements. The Milstar system is designed to work with both fixed site and mobile terminals while providing unique capabilities of which other systems are not yet capable.

When fully operational, Milstar will consist of four geosynchronous satellites providing worldwide coverage. A polar adjunct is planned to provide EHF communications to the northern polar region. Two Milstar satellites are currently in orbit,

with two more to be launched by the end of the decade in order to reach full operational capability [Ref. 24].

The first two satellites incorporate only a low data rate capability, up to 2.4 kbps. The next two, known as Milstar II, will add a medium data rate (MDR) capability of 4.8 kbps to 1.544 Mbps. Channel capacity is set at 192 LDR channels and 32 MDR channels per spacecraft (based on type of service available). This capacity will be provided via an array of antennas that provide a mix of earth coverage antennas, agile beams for concentrating service in high-use areas, narrow and wide spot beams for specialized service, and nulling spot beams for enhanced anti-jam capability in wide-area service MDR applications. [Ref. 34] Milstar I and II offer two features absent in the other two MILSATCOM systems, signal processing and crosslinking.

While other systems are transponded (DSCS III does have a limited onboard processing capability to provide anti-jam protection), Milstar signals are fully processed onboard the satellite, which allows the satellite to decide where to send the signal in order to reach to proper recipient [Ref. 32]. This also acts to remove noise from the system and reduce the bit error rate because each signal is read as a bit stream, and regenerated for transmission.

Each satellite is also crosslinked with its two nearest neighbors [Ref. 32]. This means that a separate communications channel is capable of sending bit streams to any another satellite in the constellation for downlinking back to a terminal. All users can now communicate without the use of groundstations to sort and forward signals. This reduces the number of nodes in many communications circuits resulting in lower propagation delay, and provides a survivable communications path in the event that groundstation gateways are incapacitated.

Milstar is primarily designed to communicate in the EHF band. Channel bandwidths can be as large as 2 GHz, allowing frequency hopping capability to reduce jamming and provide enhanced LPI capability in a very narrow beam. A limited crossbanding capability also exists through the use of an onboard UHF transponder. This provides a secure EHF uplink for UHF broadcast dissemination similar to the UFO EHF package. [Ref. 23]

D. INTERNATIONAL MARITIME SATELLITE (INMARSAT)

The International Maritime Satellite (INMARSAT) System is a commercial SATCOM system designed to service merchant vessels. This system uses eight geosynchronous satellites to communicate between over 2000 ship and land based terminals. INMARSAT can provide telephone, fax, video, and data to its customers via UHF and SHF-based service using L band and C band frequencies. [Ref. 23]

Individual ships are allowed to subscribe to the service. Several different grades of service are offered at data rates of up to 64 kbps. Each connection must pass from the transmitter, through a satellite, and then to a land-based station before being routed to the appropriate receiver. [Ref. 23] Because of its commercial design and international control, it can be used for administrative purposes, but not for passing tactical information or command and control data. Table 6, Chapter III, provides a typical INMARSAT link budget.

At the start of the Persian Gulf War, Navy ships did not have voice circuits available for many of the communications purposes that were readily available to land-based forces who were able to use fiber-based systems. To remedy this, many ships subscribed to INMARSAT independently. Calls were billed in terms of usage time, and the funds to pay for the service came directly out of the ship's operating budget.

Today virtually every ship in the Navy has an INMARSAT account. They are all centrally managed by Naval Space Command, but still paid out of each ship's operating funds. Tactical applications are still forbidden, and, if so used, can result in the loss of access to the system by all United States subscribers. Additionally, costs have grown to the point that they consume a large part of ship's funds. Because of this, ships have been forced to restrict usage to control spending. No increase in ship's budgets have been allowed or planned in order to provide for this service.

E. CURRENT MILSATCOM LIFETIME

Unlike many systems purchased by the DoD, satellites have a short life span. Additionally, they are expensive to procure and operate. The UFO and Milstar systems have been funded to reach full operational capability, but not for future replacements. DSCS has been in service for over twenty years, and its third generation of satellites are currently being phased in. But it too has not been funded past this point.

Current MILSATCOM systems are projected to continue to provide service until 2010, based on mean satellite lifetimes. Reliability analysis, continually being performed on these systems, projects the strong possibility that they will begin to fail sooner than 2010. Figure 6 depicts the MILSATCOM mean lifetime projected by U. S. Space Command [Ref. 19]. Other institutions provide similar projections. The diagram shows that all SATCOM assets could fall well below their capacity levels at roughly the same time, leading to a command and control crisis for the nation's military, which is increasingly dependent upon SATCOM for its timely and accurate flow of information.

Some critics point to the fact that, historically, many communication satellites far outlive their design life, such as FLTSATCOM which lasted several years longer than expected. This is an optimistic viewpoint that would produce a best-case scenario. If this is not case, the DoD must be ready to provide a replacement, otherwise a system that is heavily relied upon in tactical operations will be lost. Some capability will remain for several years, but as satellites fail, large areas of coverage will be lost. In the case of Milstar, the survivability feature of crosslinking would be greatly diminished with the loss of even a single satellite in the constellation.

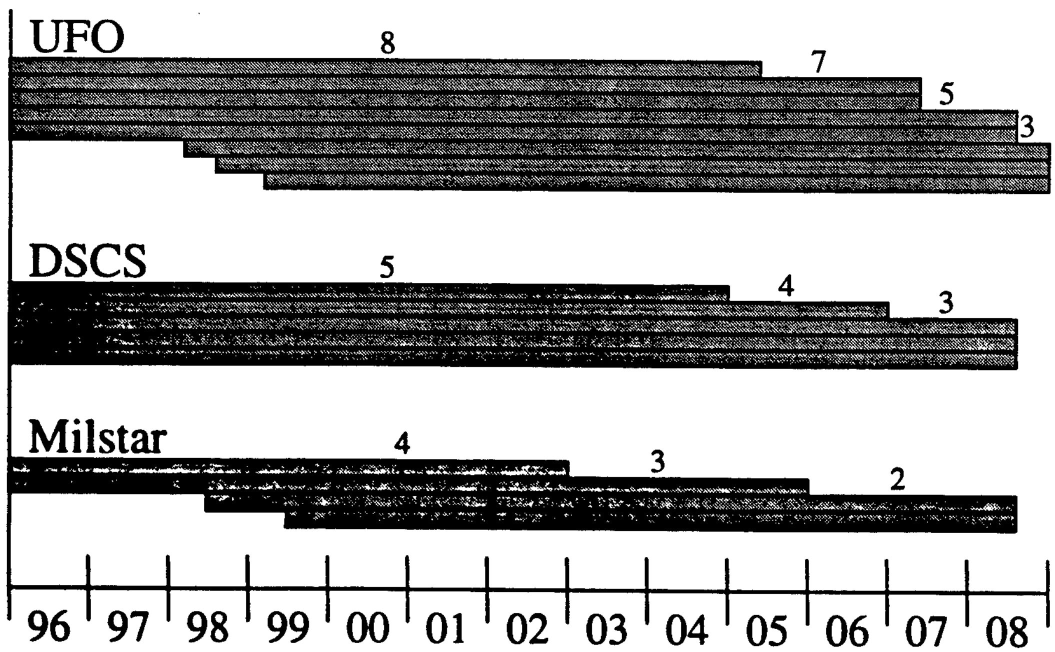

Figure 6 - Projected MILSATCOM Constellation Mean Lifetimes [Ref. 19]

Designing and fielding a replacement system is expected to take several years, and the window of opportunity is shrinking. Communications requirements already

outnumber capacity, and when individual satellites start to fail, the problem will be exacerbated. An affordable and technologically achievable solution must be settled on now, in order to provide for the needs of tomorrow.

V. SPACE COMMUNICATION TERMINALS 2000

When cellular phone systems are mentioned, most people think about small, hand-held, wireless telephones. When space-based communication systems are mentioned, most people think of satellites, and not the terminals that are actually used to establish the communication link. In fact, the lifecycle cost of acquiring, installing, and maintaining terminals often exceeds the cost of the space segment. Additionally, the fielding of these terminals is often not accomplished until the satellite system exceeded much of its useful life. [Ref. 26]

Because of the great time and expense that goes into the terminal segment, it must be a major consideration in the planning and design phase of any future system. This means looking at the current makeup of the terminal population as well as plans for the future population and composition already being implemented. Examining the past can provide insight into previous mistakes, as well as what was done correctly.

A. TERMINAL LAYDOWN

The Naval service maintains a large inventory of SATCOM terminals for a variety of applications. At the CNO level, the N63 office maintains an informal database of all terminals the Navy and Marine Corps use. This database includes a large list of individual terminals as well as upgrade programs. Tables listing terminal designations, applications, and planned acquisition through 2014 are included in Appendix C.

1. UHF Terminals

SATCOM terminals for UHF applications are by far the most numerous. They consist of shore fixed, shore mobile, airborne, shipborne, submarine borne, and manpack sets. Many terminal types are being discontinued or replaced in order to comply with JCS directives for DAMA compliance. Several of these terminals are receive only. They are designed to receive broadcast contact reporting information and for other specialized uses. Terminals that can transmit are primarily single channel capable, reflecting a capacity limitation on many current systems. Table 8 provides a brief comparison of several of the more widely used Naval UHF SATCOM terminals

Terminal	Satellite	Mobility	Uplinks	Downlinks	EIRP	G/T	EOL
AN/PSC-5	UFO	Manpack	1/DAMA	1/DAMA	18.5	-20.4	2015
AN/ARC-187	FLTSAT	Air	1	1	Varies	Varies	2009
ARC-210 (v)1	UFO	Air	1	1	Varies	Varies	2010
AN/USC-42(v)3	UFO	Air	1/DAMA	1/DAMA	Varies	Varies	2015
AN/USR-6	UFO	Air/ Ground Mobile	N/A	3	N/A	Varies	2010
AN/USC-55	UFO	Air/ Ground Mobile	1	3	Varies	Varies	2010
MATT	UFO	Air/Fixed/ Ground Mobile	N/A	4	N/A	-34.15	2008
AN/SSR-1A	UFO	Ship	N/A	1	N/A	Varies	2005
AN/USC-42(v)1	UFO	Ship	1/DAMA	1/DAMA	Varies	Varies	2015
AN/USC-54	UFO	Sub	2	3	Varies	Varies	2020
AN/WSC-3	UFO	Ship/Sub	1/Half-Duplex	1/Half-Duplex	Varies	Varies	2010
AN/WSC-3(v)XX	UFO	Ship/Sub/Fixed	Multiple/ DAMA	Multiple/D AMA	TBD	TBD	TBD

Table 8 - Characteristics of Common UHF SATCOM Terminals [Ref. 35]

2. SHF Terminals

Because DSCS satellites are designed primarily for wideband communications purposes, existing terminals do not meet LDR or mobile criteria. Navy owned SHF terminals are primarily for fixed shore locations and shipborne applications. The Marine Corps primarily uses shore-based transportable terminals and many highly transportable STAR-T terminals for use with HMWWVs that do not meet the definition for mobile. There are no plans to acquire a mobile SHF terminal due primarily to antenna size and pointing accuracy requirements. [Ref. 36]

It is worth noting that in 1993 the Air Force identified and procured a set of SHF terminals as commercial-off-the-shelf (COTS) items. [Ref. 35] As the commercial market continues to grow, it is likely that more COTS items with military applications will be available at a cheaper cost than developing new military-unique systems. Some of these may be built for, or adaptable to the mobile LDR applications that Naval forces require. Appendix C contains a complete list of SHF terminals in the Naval inventory.

3. EHF Terminals

Similar to the SHF terminals, EHF terminals are primarily aimed at fixed and transportable users. The Navy has also developed and procured a large number of ship and submarine-based units. While SHF terminals often require large parabolic antennas, EHF systems can operate using significantly smaller antennas. Common ship applications using the AN/USC-38(v)2 terminal make use of a 3 foot dish antenna to provide data rates from 75 bps to 2.4 kbps in four channels. For submarine applications, where space is at a premium, a 6 inch antenna has been designed that is capable of providing the same data rates, but to only two channels. [Ref. 35]

Similar advances are being made for transportable applications. In particular, the SMART-T and the SCAMP terminals are being developed by the Army for transportable and man-portable applications, and also will be used by the Marine Corps. The SMART-T can be HMWWV mounted for transportable applications. The vehicle must though to establish a link with the satellite. The SCAMP is a man-portable terminal that can be setup in about ten minutes. A Block I upgrade is being pursued that will reduce the weight from 37 pounds to about 15 pounds. Both of these terminals operate at the Milstar I data rate of up to 2.4 kbps. Upgrades to be compatible with Milstar II's MDR waveform have been investigated, but per unit weight would increase as a trade-off. [Ref. 35]

No other future developments that significantly alter the EHF terminal population are planned. The Navy will continue to expand its ship and submarine-based EHF capability through continued implementation and installation of its Navy EHF Shipboard Program (NESP) terminals. Some acquisitions of shore based sites to communicate with NESP equipped ships will also occur. As the Army's terminal programs begin production, both Navy and Marine Corps will take delivery of a portion of the production lot over several years to provide some degree of land-mobile requirement satisfaction. [Ref. 36] Specific long-range planning is detailed in Appendix C.

4. Commercial Terminals

Finally, there are a large number of commercial SATCOM terminals in the Navy inventory. Mobile LDR units are almost exclusively INMARSAT terminals of various types. As INMARSAT capabilities change and new services are offered, the terminal laydown will change.

Several new LEO and MEO-based SATCOM systems are expected begin service in the next decade. They will provide a variety of services and coverage options. As these services become active, it is expected that the Navy will invest in a large number of terminals to satisfy mobile LDR requirements. Because this is an unknown factor, the terminal laydown database has them currently listed as PCS/MSS terminals with no specific service provider identified. Since these will be commercially produced and publicly marketed items, little military development is required, and they are freer to take a wait-and-see attitude.

B. DEFENSE INFORMATION SYSTEMS NETWORK

The goal for military communications system is to integrate all elements into a cohesive structure called the Defense Information Systems Network (DISN). The Defense Information Systems Agency (DISA) is responsible for the effort to identify elements of a seamless, secure, reliable, and cost effective architecture that will satisfy the end-to-end needs of DoD personnel and organizations worldwide.

Current communications systems are organized under the Defense Communications System (DCS). This is a collection of many smaller systems in an attempt to link them together to provide interoperability. Many of these systems were created independently, operate on different standards, and are therefore incompatible without special translation equipment. The result is an inefficient infrastructure that needs to be overhauled to provide better service in the future.

DISA identified a baseline architecture in 1993. The objective system uses the standards associated with the Broadband Integrated Services Digital Network (BISDN) using modern asynchronous transfer mode (ATM) network implementations. Key components have been identified and are displayed in Figure 7. These components range from installed infrastructure such as major processing centers, fixed dish antennas, and fiber optic cable, to mobile components including handheld terminals, airborne terminals, and deployable switching nodes. [Ref. 35]

SATCOM services will be an important part of this architecture. Commercial and military services will be expected to be capable of interfacing with the DISN standards for effective communications. DISN will be the key element that will allow worldwide interoperability and connectivity among DoD users. To achieve this end, future terminals

must be designed to achieve a certain amount of waveform commonality and consistency that is absent under current DCS systems.

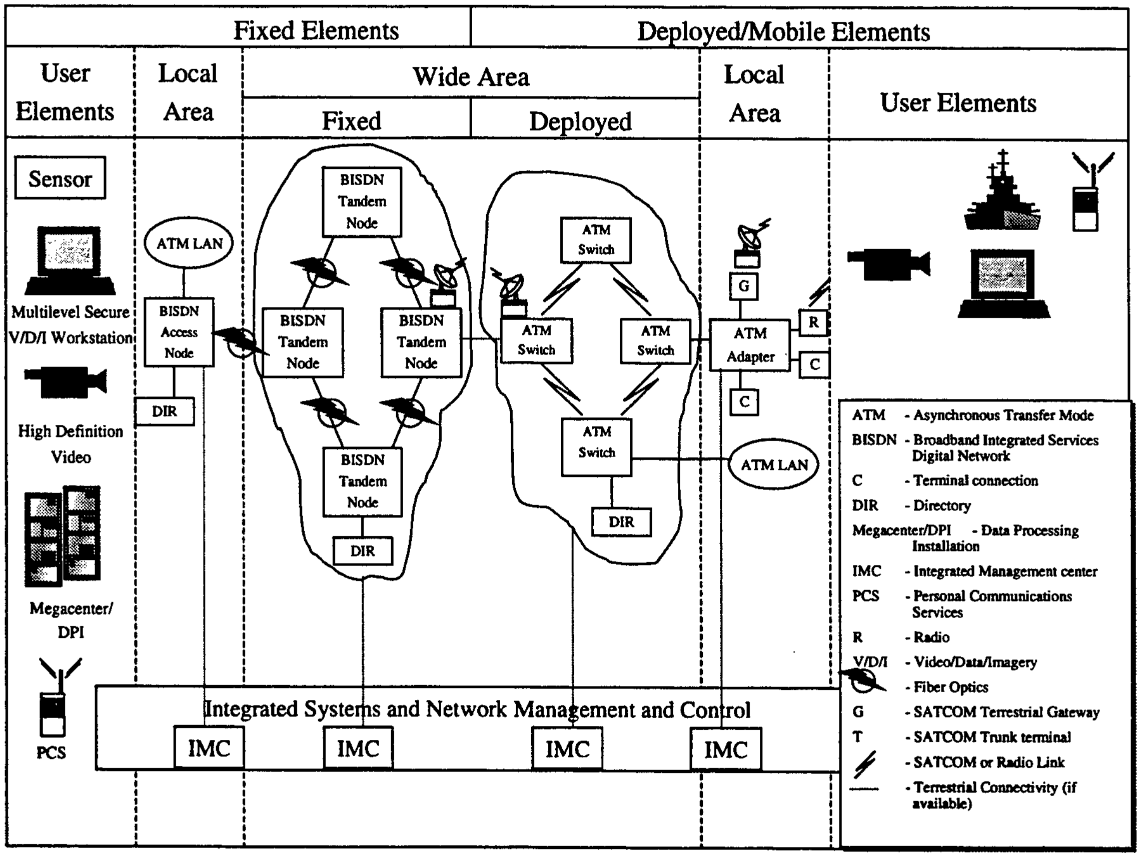

Figure 7 - Key Elements of the DISN Architectuire [Ref. 35]

In order to plan for the future, DISA led a study to identify key technologies in SATCOM necessary for achieving an objective architecture. Technical requirements were reduced to five critical issues to be addressed in any future development effort. They are:

- Manpower reduction
- Development and production cost reduction
- A "communication on the move" emphasis
- Component downsizing/ease of handling
- Terminal performance

In response to this list the government's Advanced Research Project Agency (ARPA) began a program to develop advanced technology for insertion into the MILSATCOM architecture. Called the IMPACT program for Insertion into

MILSATCOM Products of Advanced Communications Technology, it is addressing the hardware issues that need to be resolved in order to meet DISN requirements. ARPA's goal is to work with industry to provide support across the spectrum and terminal application range. They are investigating applications such as artificial intelligence, advanced circuitry, new methods for digital signal processing, and phased array antennas for SATCOM use. [Ref. 35]

C. JMCOMS/ADNS

As part of a restructuring of its communications network capabilities, the Navy has instituted the Joint Maritime Communications Strategy (JMCOMS). JMCOMS is both a technical and program strategy which incorporates the latest advances in commercial and military communications technology to maximize bandwidth for enabling the sharing of information seamlessly, in real-or near real-time, through flexible, adaptive, and interoperable systems and services. It is designed to provide both tactical improvements to the warfighter and non-tactical quality of life services to sailors at sea and ashore. [Ref. 37]

The Automated Digital Network System (ADNS) is the backbone to JMCOMS. ADNS uses off the shelf protocols, processors and routers to create a robust and flexible networking environment. Internet Protocols (IP), ATM, and other products are being adopted or adapted from the commercial telecommunications world. Interfaces to all RF media provide the throughput and access needed. At the same time, networking techniques are designed to make efficient use of all available channels. [Ref. 37]

The ADNS represents the Navy's contribution to the proposed DISN. The network control hardware depicted in the 'deployed' segment of Figure 7 will be based on ships in the operating theatre. Users will be able to communicate via direct line-of-sight or SATCOM link with the ADNS node, which will allow addressing and routing to the proper recipient.

This system can help offload some communications and processing requirements from the satellite constellation, as well as provide SATCOM capability to users not equipped with SATCOM terminals. This system will help the Naval service to build towards a common waveform, or set of waveforms that can be carried over into a future objective architecture.

VI. ARCHITECTURE 2010

Developing an objective communication architecture to satisfy the varied needs and uses of all components of the Department of Defense is an enormous undertaking. It is important to realize that not all requirements will be satisfied because requirements are a prediction of the future and never completely accurate, and the complexity of the problem makes complete satisfaction very unlikely. Additionally, the current rate of technology growth outpaces the speed of the military systems acquisition and fielding process due to long development timelines and budget constraints. With these facts in mind, it is important to provide a system that will provide the best service available within the budget limits imposed by Congress.

A. REQUIREMENTS REVIEW

Prior to developing architecture options to satisfy Naval mobile LDR requirements, it is important to review some of the major architecture drivers presented in this thesis. These are not "build-to" specifications, but rather descriptors of the types of service to be provided, as well as physical, political, and financial constraints that will affect the system during its life-cycle.

The DoD's Mobile User Study has laid out the top level system requirements and their order of precedence. This list is designed to meet the needs of all of the services, not just those of the Naval Service. The list is reproduced here.

- Assured Access
- Netted Communications
- Communication on the Move
- Joint Interoperability
- World-Wide Coverage
- Point-to-Point Communications
- Broadcast Capability
- Polar Coverage

It is important to note that this list represents types of service or quality expectations. These items are too vague to be verifiable elements of the system. Instead,

they are used to provide direction and aid in developing more detailed circuit requirements.

The ERDB is the document that provides the necessary circuit level detail. It list individual circuits and their varying levels of service requirements. This document can be used to determine aggregate throughput requirements and levels of protection. It does not however provide a regional breakdown or a global perspective of the SATCOM need.

Many of the larger issues such as survivability, compatibility with legacy systems, wave forms, and encryption methods are addressed in broader documents such as the Capstone Requirements Document or the Functional Requirements Document. In short, there is no single source for requirements because there is no consensus from the users. This leaves a lot of room for architecture trade by developing agencies, but also leads to the possibility that no system can be developed to adequately satisfy many user needs.

The two components of an objective architecture that interest the user are the space segment and ground terminals. In the past, terminals were developed to utilize the services that a satellite system could perform. This led to a large number of terminal programs and a lack of interoperability between them. Today's requirements combined with past experience suggest that terminals should be developed first to meet user needs. Satellites should then be developed to complement the capabilities of the terminals for closing the communication link. This should not be a waterfall process, but an iterative loop aimed at capitalizing on the advantages offered by each segment, as depicted in the system engineering process.

B. OFFICE OF THE SPACE ARCHITECT

In September of 1996, the DoD Office of the Space Architect (OSA) released a brief summarizing SATCOM issues and addressing the need for a follow-on architecture. The report was the result of months of work aimed at identifying a path to solve this problem. Instead of proposing an objective architecture though, the brief outlined four possible directions for the DoD to take. These options, along with projected relative costs are depicted in Figure 7. [Ref. 38]

Alternative A is the baseline system, and is based upon the systems that will be in place at the turn of the century. The concept is to keep UFO, DSCS, and Milstar in place for the long term by funding the purchase and operation of further satellites to extend constellation life, as well as progressively upgrade future satellites. This is seen as a low-

risk option because the technology has already been developed, and the operators are familiar with the equipment. Infrastructure is already in place, so up-front costs would be minimized. Projected cost for 20 years of operation is $55 billion.

Although this alternative is relatively low-cost, it does not address the fundamental problems with current systems: capacity, mobility, and interoperability. Taking this approach would only serve to prolong and exacerbate these problems. These systems were designed to operate in a world of low demand, but the current state of rapidly increasing channel and performance requirements have already overcome system capabilities.

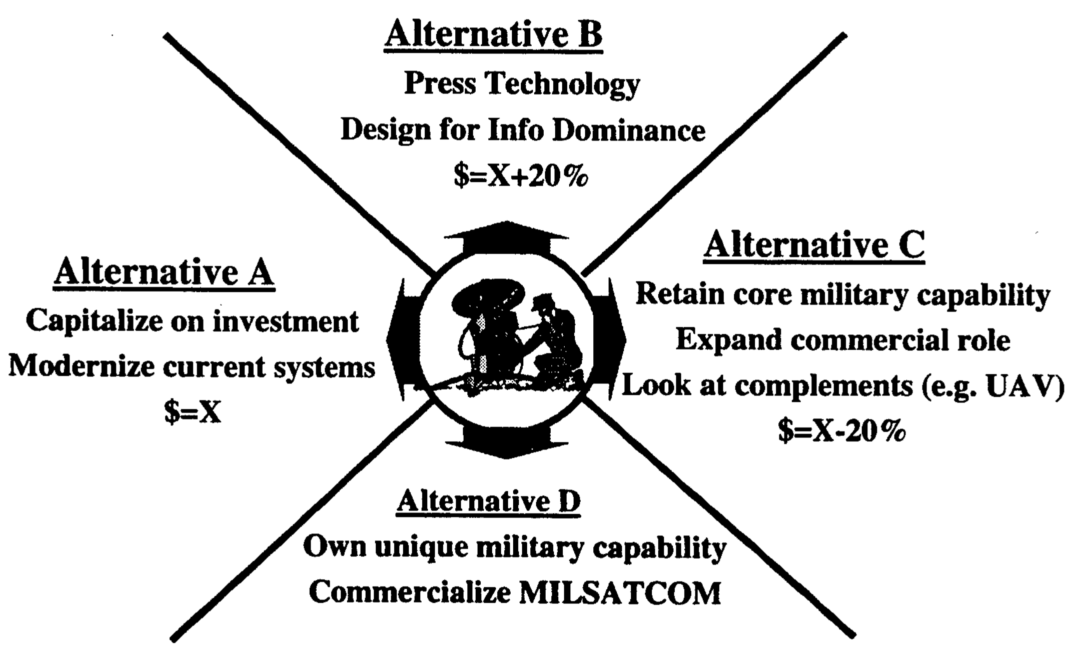

Figure 8 - OSA Architecture Options [Ref. 38]

Alternative B represents a redesign of MILSATCOM to take advantage of the capabilities provided by emerging technology. This means completely redesigning both the space segment and the terminal segment to utilize advanced concepts such as phased array antennas, laser crosslinks, and full on-board processing to provide greater service. This is a riskier option due to the reliance on unproven concepts, but commercial industry has been working hard to develop many of these concepts in order to provide commercial SATCOM services, so much of the development research has been done. The utility of such a system to the DoD services, however, is much higher than any other option. OSA predicts a 20-year life-cycle cost of $67 billion.

Alternative C is based upon a mixture of MILSATCOM and commercial SATCOM services. This alternative envisions a MILSATCOM capability similar to current systems, with augmentation from one or more commercial systems, and possibly Unmanned Aerial Vehicles (UAVs) to fill gaps in service or coverage. The result is less infrastructure for the DoD to manage, and less risk of failure, but an increased reliance on the commercial market to meet the military demand, possibly at the expense of satisfying commercial customers. Projected costs for twenty years are $51 billion, but that figure is highly dependent upon what commercial vendors can provide, as well as the cost of their hardware and services.

The final choice, alternative D, is to rely exclusively upon commercial SATCOM services. This includes the possibility of selling military spectrum allocation to commercial vendors and then leasing back services. This move is seen as providing cost savings in the short term because the military would not have to devote resources to build and operate the system. On the other hand, the DoD would be forced to rely on the services provided, as opposed to the services it needs. In such a scenario, the DoD may be forced to compete with commercial customers for access, and could be forced to spend money to buy equipment compatible with one or more systems that may not be interoperable. Long-term costs could escalate far beyond some of the other alternatives, but current 20-year life-cycle costs are estimated by OSA to be about $61 billion.

C. COMMERCIAL COMSAT

The use of commercial COMSAT services appears in two of the four OSA alternatives. As of this writing, the commercial sector primarily provides SATCOM services to non-mobile users via geosynchronous orbits. However, several LEO and MEO constellations designed to provide mobile service are in various stages of planning in order to begin providing service during the next decade.

These emerging Mobile Satellite Systems (MSSs) are aimed at tailoring their services to satisfy the needs of the commercial rather than the military market. Their goal is to provide regional or worldwide point-to-point telephone coverage, as well as a link to the Public Switched Telephone Network (PSTN). Each service operates within its own spectrum allocation and uses proprietary hardware. They are not interoperable, but can call each other via a PSTN link.

In order to secure frequency rights into the many countries in which they wish to offer service, MSS providers have agreed to work with local mobile service providers and telephone utility companies. In most cases, a satellite will receive a request for service from a subscriber, collect billing, location, and authorization information, then attempt to route the call through a local terrestrial network. If such a network is unavailable, the call can be routed through satellites and ground station gateways to an appropriate entry point to the PSTN. A single billing point receives payment and distributes it to all nodes entitled to a portion of each call. MSS is designed for point-to-point communications and paging, and there are currently no plans to provide netted service.

MSSs are expected to be capable of satisfying many of the circuit requirements listed in the ERDB for point-to-point communications. They can provide telephone type access from a single address or phone number to virtually any place on Earth. Using them to fulfill administrative communications can aid in relieving congestion on MILSATCOM assets and provide a short-term surge capability, but there are many features, or lack of features, that make them unsuitable for tactical applications.

First of all, although some planned constellations will make use of satellite crosslinks, many will not, and therefore require the presence ground station gateway within the satellite cell footprint for call routing. This means that a battlegroup at sea may need to carry a mobile gateway in order to ensure access in areas not covered by land based gateways. The DoD would need to maintain several of these mobile gateways to guarantee access in all remote locations.

Because MSSs are for profit, many of them tailor coverage to areas of high population. For instance, polar and ocean areas have few possible customers. Some systems are designed to slew their receivers away from these sparse regions to higher population centers within their access areas. This works to the disadvantage of Naval forces that operate in the open ocean, polar regions, and other remote locations. Although the capability exists to slew coverage to these areas, it would come at the expense of commercial customer service, and therefore carry a premium price.

In order to ensure accurate billing, proper call routing, and provide incoming call service, MSSs must know the location of its users. Most accomplish this by sending a locating signal to the constellation from the handset when it is turned on. This flow of geolocation information would not be controlled by the U. S. government and would lead directly into the host country's gateway system. Clandestine operators such as Special Operations Forces would be unable to maintain secrecy and be exposed to enemy forces.

Finally, such a fee-for-service approach could potentially drive long-term costs up precipitously. Commercial SATCOM services such as the planned Iridium constellation expect to charge approximately $3 per minute of use. For a netted circuit operating on 24 hour basis, this amounts to $4,320 per day for each user. When multiplied by the number of worldwide users and nets, the costs can add up quickly. Although not developing, launching, and maintaining the space segment would save money in the early years, those costs could eventually be more than offset by the cost of operation.

All of these factors, combined with other problems such as encryption compatibility, competition for access with commercial users, and the ease of signal interception combine to make commercial MSS a poor choice for military tactical applications. They should not, however, be overlooked as an alternative for non-tactical applications. Almost any application that can be suitably satisfied by the PSTN is a candidate for MSS. Many mobile applications that make use of today's terrestrial based cellular networks or INMARSAT are good nominees for migration to a commercial MSS in the future to both maintain mobility and relieve MILSATCOM requirements.

D. ARCHITECTURE COMPONENTS

Regardless of who operates a communication system, the potential components of any architecture chosen are relatively similar. Options for facilitating low data rate mobile communications range from terrestrial through airborne, to space based platforms.

Terrestrial options include currently used direct line-of-sight from user to user, as well as fixed or portable repeater stations similar to modern cellular systems. These options will still limit range though because of a limited radio horizon due to their low altitude, and the high potential for interfering obstacles. There is also the problem of establishing repeater stations in denied territory.

Using airborne assets for communications processing or relay is becoming an increasingly attractive option. Using airplanes in this role is a possibility, but could prove expensive to provide assets, maintenance, personnel, support, and training. Additionally, having communications planes flying over or near a battlefield could provide an easy target to enemy forces. A more suitable alternative would be the adaptation of UAVs or long endurance balloons in this role.

Some modern UAV platforms have the capability to loiter at high altitudes up to 80,000 feet or more, for greater than 24-hour periods without refueling. Also, helium

filled balloons powered by solar energy are capable of staying aloft at the same altitudes for much greater periods of time [Ref. 39]. Higher altitudes would provide a much greater radar horizon and access area to the UAV. This would work to keep the UAV out of almost any missile envelope, allow it to provide service to a greater area, and enable it to maintain greater lateral separation from the battlefield.

As a communications link, a UAV could provide two services. First, it could act as a direct relay, receiving user data streams and retransmitting them back to ground based terminals. Second, it could perform as an intermediate relay between ground and space based assets. This could reduce the power required from disadvantaged portable terminals, while still allowing them to close a SATCOM link.

The major drawback for a UAV-supported system is that a launch and control platform would need to be located near the operating region in order to provide service. This would not be a problem in areas of major military operations, but could prove difficult for smaller diplomatic or SOF requirements in denied access territory.

The final option for locating communication link control devices is space. The relative merits and drawbacks of the major orbital regions are discussed in chapter 3. Space-based assets are generally accepted as the preferred solution for providing communications links. Once in place, these assets provide service that is transparent to the user, and can allow users to link to virtually any other communications node in the world. They are, however, expensive to purchase, launch, operate, and replenish.

No matter what environment, or mix of environments, is chosen to support an objective SATCOM architecture, terminals are required. These terminals must meet a wide range of applications, from handheld, to ship-based, to aircraft-based, and fixed land-based. In addition, they must remain interoperable to allow a myriad of users to communicate effectively, as well as be backwards compatible with legacy systems to support a transition to new systems and wave forms.

Large costs will be associated with the development, purchase, fielding, and support of new terminals. In order to streamline the acquisition, support, and repair efforts of a smaller, more efficient military, commonality of standards, parts, and operations must be aggressively pursued. Great care must be taken to avoid mistakes of the past in developing stove-pipe systems that hinder broad communication applications and reduce tactically efficient application.

E. OBJECTIVE ARCHITECTURE PROPOSAL AND TRADES

An objective architecture is one that will satisfy as many requirements as possible within the financial, technological, and political constraints imposed upon the system. Within the scope of alternatives proposed by the Office of the Space Architect, alternative B offers the greatest utility to military forces as an objective, as long as risks are aggressively managed. Although the cost may be higher, it is worth the price in order to move away from today's stove pipe systems, to a unified, interoperable system that will allow all branches of the military to work together to wage coordinated warfare.

To that end, the objective system for 2010 should be a LEO or MEO constellation tied together by satellite crosslinks to provide tactical communications, augmented by commercial MSS to provide for administrative services. This would provide a world-wide MILSATCOM capability to operational forces, while using commercial assets to help offload non-operational traffic to free bandwidth.

Constellation size would be based upon orbit altitude in order to meet coverage and frequency reuse requirements. Each satellite would be capable of handing off signals to a neighboring satellite as it approached its radio horizon. The crosslinks would allow satellites to act as network routers, passing signals addressed to users located within another footprint. Phased array antennas would be used to allow agile beam patterns to produce selective coverage in a system with high relative motion.

Each satellite should be designed with onboard processing to provide signal handling without ground station interference. Network controllers would assign user priorities and designate which users are allowed access to which communications nets or services. Users desiring access would send a handshake signal to a local satellite containing an address or user code, and a request for service via a TCP/IP type protocol. Onboard logic would determine whether or not the user has the proper priority and authority to receive the requested service. If so, the requesting terminal would be assigned a channel frequency and bandwidth based upon service requirements and terminal capability.

This type of architecture would rely on crossbanding and bandwidth-on-demand to satisfy user requirements. Crossbanding would allow users of differing terminal types to communicate in a spectrum band most advantageous to them. The satellite constellation would be responsible for translating received signals to the proper frequency for the downlink. Bandwidth-on-demand would allow each user access to the maximum

bandwidth available based upon their priority, terminal capability, and overall demand for service within the same geographic region. Initiation of higher priority circuits could force those of a lower priority to be preempted in a band limited region. Implementing these types of features would provide a high degree of flexibility in allowing theatre commanders control over communication assets available to them.

A system such as this would allow a wide range of terminals to be used. Highly mobile disadvantaged users could make use of dipole antenna equipped handheld terminals to communicate with larger parabolic dish equipped terminals operating in the SHF or EHF spectrum. This would allow each user to maximize communication capability within the relative limits or advantages of their operating capabilities. Additionally, advancements in terminal technologies such as smaller phased array antennas could allow greater flexibility to be built into smaller terminals.

This would be an expensive undertaking. New terminals, procedures, and logistics capabilities would have to be put in place, and more satellites would have to be launched both to populate and replenish the constellation. Advances in technology and production methods could offset many of these costs. The commercial SATCOM industry is already building towards this type of space-borne network. The military acquisition system would be poised to take advantage of technology and components that have already undergone development by industry, to include handheld SATCOM terminals and assembly line produced satellites.

If despite the high utility of such a system, the government is unwilling to make such a large investment, trade-offs could be made. The most obvious trade would be to raise the constellation altitude toward GEO, thereby reducing the number of satellites and launches required. Dollars would be saved, but system performance would suffer in terms of frequency reuse, propagation delay, coverage, and power or antenna sensitivity required to close the communication link.

Some of these deficiencies may be at least partially overcome by augmenting the system. For instance, UAVs could be used as a relay between ground and space base nodes. They could also be used in place of satellites to provide an increased capability in regions of high density radio traffic. Also, polar adjunct satellites may be added to the constellation in HEO or Molniya orbits to satisfy polar requirements.

Although these trades are available, they are not desirable. The less performance that is built into the system, the lower the utility of the system is to the user. Today's legacy stovepipe systems, while useful, are far from providing a coherent, interoperable

capability to the mobile user. Continuing down that path because it is a cheaper alternative will only increase the problem in the future as force structure continues to diminish, while communications requirements continue to rise at an increasing rate. Relying on commercial capacity for tactical applications would reduce infrastructure and fielding costs, but could prove much more expensive due to high usage fees, while forcing the military user to compete with commercial subscribers for access. The creation of a military unique, technologically advanced SATCOM system may be expensive, but it would open the door to a long-term capability that would serve to enhance and optimize the warfighting capabilities of the U. S. military services.

F. GAPFILLER

No matter what option is chosen to satisfy future SATCOM requirements, a smooth transition that does not disrupt tactical applications is necessary in the author's opinion. Due to a late development start and the possibility of one or more current constellations losing capacity due to failure, an effort must be made to prevent gaps in service. To meet this end a gapfiller plan is be necessary.

Options for providing gapfiller service include funding further launches of current systems, leasing bandwidth on commercial systems, and launching an intermediate MILSATCOM capability to bridge the difference in services provided by the current and objective systems. The chosen route will depend upon the design of the objective architecture and its operational timeline compared to failure predictions of current systems such as the one depicted in Figure 6.

G. VERIFICATION

An important consideration in development of any new system is verification of performance. The problem is assuring that a proposed system will meet its intended objectives. This is generally accomplished via a rigorous test and evaluation plan.

To make this work efficiently, the system must be designed with testing in mind. This means including personnel from the test community in the early stages of design and development. They can provide guidance from requirements generation through design and construction in order to make testing run more smoothly, and to provide meaningful results on which to base decisions.

Most military systems are purchased in large quantities, so tests can be performed on production representative articles. Satellites, however, are generally produced in very small quantities, so it is difficult and prohibitively expensive to launch an article into orbit for testing. This means that maximum use must be made of ground-based tests, equipment, and simulation.

Many tests today are based upon simulation and modeling. Modern computer hardware and software are capable of providing very robust simulations of satellite communication systems. In fact the military has entire commands devoted to the practice of modeling and simulation. These people need to be utilized early in the development life cycle so that problems can be discovered and changes made early in the process.

Additional testing can be done using test bench equipment at the component level. These are used to verify component performance on an individual basis. Testing must be continued as components are integrated in order to prove compatibility of interfaces.

Finally, do not forget the system component of greatest interest to the user, the terminal set. The user is not interested in how the satellite accomplishes its task, but rather the end result. All terminal designs must be able to meet requirements for operational effectiveness and suitability in order to satisfy the user's needs.

Any system or requirement that cannot be tested cannot be shown to meet its specifications. Fielding such a system, while not precluded, increases the risk that requirements will not be met. With a system expected to cost in excess of $50 billion over twenty years, not adequately planning and testing in order to verify performance is an unacceptable error, with the potential to compromise the effectiveness of U. S. tactical efficiency.

VII. CONCLUSION

The issue of military space-based communications is extremely complex and divisive. The technology and user requirements are continuing to grow at a much faster rate than the mechanisms to deal with them can handle. Within the Department of Defense, many different agencies are attempting to arrive at solutions to the problem of providing a continued SATCOM capability to military forces. These agencies are competing for limited budgets and authority in order to obtain their own objectives. The problem is that few of these agencies are working together to find solutions. This leads to duplication of effort, as well as wasted time and money.

At the Secretary of Defense level, DUSD (Space) is responsible for overseeing SATCOM development and planning efforts. This office needs to take the necessary steps to streamline and coordinate all SATCOM efforts within the DoD. Although some competition among agencies is good in order to provide a constant challenge to produce quality work, the current situation needlessly consumes scarce resources. An aggressive reorganization is needed in order to provide clear lines of authority and responsibility aimed at solving a common problem.

Because of their different roles, each service has a different set of requirements and priorities. This can be seen by re-examining the MUS requirements voting matrix listed in Table 3. In this case the Air Force has listed communications on the move and joint interoperability considerably lower than the other services. This reflects the differences in the operational roles between the Air Force and the other services. They will not be willing to spend money for services they do not value highly, at the expense of those services they see as more beneficial.

When systems destined for joint use are acquired and fielded, a lead service is designated to spearhead the effort. Often, this service must provide a larger share of the system budget than it feels is fair, but in return it often gets greater control of the project. In the author's opinion, when a system such as a proposed joint SATCOM system finally enters development, no single service will want to take money from other projects to support it. The end result can be a fielded system with reduced performance and utility to the user, or no system at all.

To prevent this from happening, acquisition for this type of joint system should be managed and funded by an OSD level agency such as DISA. The project would be

staffed by appropriate military and civilian personnel trained to work within the military acquisition process, but would not be in the direct reporting chain of any of the services. While not guaranteeing any impartiality, this would be a step in the right direction.

While researching this topic it has become apparent that the management of future requirements is not very well controlled. The recent creation of the ERDB is a move to formalize the process, but it is not complete. Within the Navy and Marine Corps, the ERDB is a very informal document managed by a small group of people at Naval Space Command. There is no official governing instruction or guideline for operational personnel to submit and document requirements for several years into the future. Part of the problem may be that most operational commanders are much more concerned about near term requirements than those so far in the future. Steps need to be taken to continue to formalize or standardize this process not only within Naval forces, but throughout DoD, in order to support long range planning of systems that will adequately meet user needs.

Within the MUS process a relatively small group of people is working under a greatly compressed timeline to provide a plan for supporting future mobile SATCOM needs. The MUS, however, is part of a larger, OSD level study that encompasses SATCOM requirements beyond the mobile low data rate problem. Working independently, these groups will arrive at discrete solution sets that will satisfy their individual pieces of the puzzle. This is a bottom-up process that is likely to produce a set of systems that either duplicates functions, or is not interoperable, and will require further iterations, time, and money to arrive at a final solution. A better alternative may be to provide greater visibility and direction from the top level, much like the Systems Engineering process previously discussed. The goal should be to optimize the performance of the entire system rather than optimizing the performance of its individual components.

Whatever conclusion is reached through this process, it is important to be sure that the user receives the product that will provide the highest utility in the operational environment. Cutting corners to realize savings in the short term could prove costly in the long run. It is also important to remember to keep an open mind and not unnecessarily restrict the set of possible solutions. Satellites are not the only answer. Assets such as UAVs and other sub-orbital platforms may be capable of providing service with a high utility at considerably lower cost.

It is prudent to once again note that the commercial mobile SATCOM industry is getting ready to explode. Recent changes in technology have prompted many organizations to prepare to field their own LEO and MEO based MSS. Although these services are not a panacea for the military operator, they may be able to provide some support. Even though their security features, coverage areas, and services offered will be unable to fulfill the needs of many military circuit requirements, they may prove to be of great use for administrative applications, providing relief for burdened MILSATCOM assets.

An attempt to define an objective architecture that will satisfy MILSATCOM requirements for 2010 must keep all of the preceding factors in mind. Although some alternatives may be cheaper or more politically acceptable, they must be critically examined against some of the tougher alternatives. Today's MILSATCOM architecture was built to an older set of standards, in an environment where SATCOM was relatively new. A new objective architecture can choose to stay the course already set and evolve the current architecture into a more usable format, or it can be a move to revolutionize and reinvent the way the Department of Defense operates its communications systems.

Current systems will eventually need replacement. The coincidental expiration of the major space components of the current architecture provides the military with a unique opportunity. Now is the time to institute a revolutionary system with the provisions for growth and interoperability that today's systems lack. It many be a more expensive undertaking, but if properly managed, can provide unprecedented operational utility to the warfighter.

Commercial industry has paved the way for the operation of LEO and MEO-based satellite systems that provide global coverage. The space-based components, terminals, and operating concepts of these systems are just now coming online. This puts the military in the position of being able to take advantage of COTS and non-developmental item purchasing, as well as an industrial base on the verge of mass-producing communications satellites. The final piece of the puzzle will be the development of launch systems capable off placing satellites in orbit at much cheaper costs. If this can be achieved, there should be no obstacles remaining to the pursuit of a large LEO or MEO constellation as long as the user communities can come to terms with each other and provide a comprehensive set of requirements.

Affordable and reliable space-based communications systems that can satisfy the mobile LDR requirements of Naval forces are about to become a reality. With these

types of services available on the open market it would be a mistake to pass up the opportunity to usher in a new era in communications capability that could greatly enhance the battlefield effectiveness and survivability of U. S. troops. Future foes ranging from national armed forces to small terrorist organizations will be able take advantage of these services. Will the United States provide its troops with the tools they need to combat these forces?

APPENDIX A - ERDB LOW DATA RATE REQUIREMENTS

This appendix contains data from version 2 of the Emerging Requirements Database. Only low data rate ($\leq$ 64 kbps) requirements are listed for both Navy and Marine Corps Forces. The significance of this information is discussed in chapter II. Some ERDB classification definitions are provided below. [Ref. 17]

- **Type Ops**:
  - **Full Duplex Link** - Communications link in which information can be transmitted both ways simultaneously.

  - **Half-Duplex Link**- Communications link in which information can be transmitted both ways, one direction at a time.

  - **Simplex Link** - Communications link in which information travels one way only. One station transmits while another, or several others, receive.

- **Availability**:
  - **On Call** - A link in which transfer of information is not continuous throughout the day. The requirement is activated and released on demand, or could be supported by an on-demand, use-and-release type of communication system such as DAMA. High priority users will be guaranteed assured access. All other users will be serviced based upon priority and channel loading. All users can expect to receive adequate service in terms of average queuing delay.

  - **Full Period** - A link in which transfer of information is continuous or near continuous. Once activated, the link is not released until the end of the request period. Satellite capacity must be reserved for the requirement, whether or not traffic is flowing.

- **Connectivity**:
  - **Broadcast** - A communication topology that allows a single user to communicate a common data stream to many users (one to many).

- **Netted/Conference** - A communication topology that allows multiple users to communicate on a common data stream (many to many).

- **Point-to-Point** - A communication topology that allows two users to communicate only with each other (one to one).

- **Protection requirements**:
  - **Anti-Scintillation/Hemp** - Protection level where protection is required against the scattering effects of nuclear detonations on communications signals. In addition, the circuit must be able to survive the effects of a high altitude electromagnetic pulse (HEMP).

  - **Anti-Jam Sanctuary** - Protection level where protection is required against a high power fixed jammer located in an unfriendly country, usually not near the friendly terminals that are being jammed. Effective power is equivalent to the fixed jammer threat postulated by DIA for the frequency band of interest.

  - **Anti-Jam Tactical** - Protection level where protection is required against a medium power jammer, usually on a mobile or transportable platform. Effective power is equivalent to the maximum shipborne or ground transportable jammer threat postulated by DIA for the frequency band of interest.

  - **Anti-Jam Nuisance** - Protection level where protection is required against a medium or low power deliberate or unintentional jammer whose power level is comparable to that of the friendly terminal being jammed.

- **Low Probability of Intercept/Low Probability of Detection (LPI/LPD)** - Denying a hostile collection and monitoring platform form ascertaining the technical parameters of a transmitted signal other than its presence or carrier frequency. The ability to transmit communications signals within a specified distance of hostile monitoring platforms without the signal being detected by the "bad guy".

- **US Control** - The United States government has the ability and mechanisms needed to effectively plan, monitor, operate, manage, and manipulate the available resources.

- **Duty Cycle** - The ratio of the amount of time that a communications link is activated to the total time period.
  - **<100%** - Indicates that the link is activated less than full time.
  - **100%** - Indicates that the link is activated full time.
- **Requirement Multiplier** - The numbers of this type of circuit needed to satisfy all requirements for this unit.

Ref		JCS			Data	Type Ops			Avail		Connectivity			Protection Requirements							SATCOM			Service Provided						
					Rate	Duplex			On	Full	Bd'	Net-	Point/	AS -	Anti-Jam			LPI	US		Wide	Nar	Pro-					Duty Cycle		Req
#	Category	PRI	Unit	Nomenclature	(KBps)	Full	Half	Simp	Call	Pd	Cast	ted	Point/	Hemp	San	Tac	Nus	LPD	Ctrl	None	Band	Band	tected	Voice	Data	Video	Comb	<100%	100%	Mult
038	JTF / CTF Ops	2D	Fleet	Allied / JTF Conn (Data)	64		1		1			1							1			1			1			25		1
039	Comp Suppt	2E	Fleet	SATHICOM (Voice)	2.4		1			1		1							1			1		1				50		1
040	Comp Suppt	2E	Fleet	Fleet / JTF Cmd (Voice)	2.4		1		1			1							1			1		1				50		1
041	Comp Suppt	2E	Fleet	Fleet / JTF Cmd (Data)	64		1		1			1							1			1			1			75		1
043	Comp Suppt	2E	Fleet	Broadcast	64			1		1	1								1			1			1				1	1
045	JTF / CTF Ops	2D	Fleet	Flt / JTF Admin / Log	2.4		1		1			1							1			1		1				50		1
046	JTF / CTF Ops	2D	Fleet	Flt / JTF Admin / Log	32		1		1			1							1			1			1			25		1
072	Comp Suppt	2E	Fleet	Mobile Satellite Svc	2.4		1		1				1						1			1		1				5		2000
074	Comp Suppt	2E	Fleet	SATHICOM (Voice)	2.4		1			1			1	1									1	1				25		1
079	Strat Rpt Bk	1D1	Fleet	SSBN Report Back	2.4		1		1				1	1									1	1				10		10
080	Strat For Dir	1C1	Fleet	SSBN force Direction	2.4		1		1				1	1									1	1				10		10
081	Comp Suppt	2E	Fleet	SSN Report Back	2.4		1		1				1	1									1	1				10		20
087	JTF / CTF Ops	2F	Fleet	Allied / JTF Connect	2.4		1		1			1							1			1		1				25		1
088	JTF / CTF Ops	2F	Fleet	Broadcast	64			1		1	1					1							1		1				1	1
089	JTF / CTF Ops	2F	Fleet	Mob Sensor TIP	19.2		1			1		1							1			1			1				1	1
Fleet			TTL:	328.8		0	13	2	10	5	2	8	5	4	0	1	0	0	10	0	0	10	5	9	6	0	0	12	3	
			Ckts:	15		0%	87%	13%	67%	33%	13%	53%	33%	27%	0%	7%	0%	0%	67%	0%	0%	67%	33%	60%	40%	0%	0%	80%	20%	

Table 9 - General Fleet Communication Circuit Requirements

Ref #	Category	JCS PRI	Unit	Nomenclature	Data Rate (KBps)	Type Ops Duplex Full	Type Ops Duplex Half	Type Ops Simp	Avail On Call	Avail Full Pd	Connectivity Bd' Cast	Connectivity Net-ted	Connectivity Point/ Point/	Protection Requirements AS - Hemp	Anti-Jam San	Anti-Jam Tac	Anti-Jam Nus	LPI LPD	US Ctrl	None	SATCOM Wide Band	SATCOM Nar Band	SATCOM Pro-tected	Service Provided Voice	Service Provided Data	Service Provided Video	Service Provided Comb	Duty Cycle <100%	Duty Cycle 100%	Req Mult
014	Comp Suppt	2E	CVBG	CVBG Secure Voice	2.4		1		1			1			1								1	1				50		1
016	Comp Suppt	2E	CVBG	Airwing Strike	2.4		1		1			1							1			1		1				50		2
017	Comp Suppt	2E	CVBG	ASW (Voice)	2.4		1		1			1							1			1		1				50		1
018	Comp Suppt	2E	CVBG	ASUW (Voice)	2.4		1		1			1							1			1		1				50		1
019	Comp Suppt	2E	CVBG	AAW (Voice)	2.4		1		1			1							1			1		1				50		1
020	Comp Suppt	2E	CVBG	Information Ops (Voice)	2.4		1		1			1							1			1		1				50		1
021	Comp Suppt	2E	CVBG	LAMPS Data Link	64		1		1				1						1			1			1			75		5
022	Comp Suppt	2E	CVBG	SONAR Data Link	64		1		1				1						1			1			1			75		2
023	Comp Suppt	2E	CVBG	UAV Control	32		1			1			1						1			1			1				1	2
026	Tac Warn / Int	2F	CVBG	CVBG SI Common	2.4		1		1			1							1			1		1				50		1
027	Comp Suppt	2E	CVBG	Cruise Missile Satellite Data Li	32		1			1		1							1			1			1			50		10
029	Comp Suppt	2E	CVBG	CSEL	4.8		1		1			1							1			1			1			05		1
030	Comp Suppt	2E	CVBG	BGIXS	64		1			1		1							1			1			1				1	1
031	Comp Suppt	2E	CVBG	LINK-16 (JTIDS)	64	1				1		1							1			1			1				1	1
032	Comp Suppt	2E	CVBG	NTDS LINK-11	32	1				1		1							1			1			1				1	1
033	Comp Suppt	2E	CVBG	SABER	4.8	1				1		1							1			1			1				1	1
034	Comp Suppt	2E	CVBG	CVBG SEAL / SOF Net	2.4		1		1			1							1			1		1				10		2
036	Tac Warn / Int	2F	CVBG	Remote / Unatt Sensors (Afloat)	9.6		1		1			1							1			1			1			10		1
037	Comp Suppt	2E	CVBG	EOD Net	2.4		1		1				1						1			1		1				50		1
075	Comp Suppt	2E	CVBG	CVBG Cruise Missile MDU	16		1		1				1	1									1		1				1	5
077	Comp Suppt	2E	CVBG	CVBG SEAL / SOF Net	2.4		1		1			1				1							1	1				10		2
083	Comp Suppt	2E	CVBG	CVBG Command	2.4		1		1			1			1								1	1				50		2
084	Comp Suppt	2E	CVBG	CVBG Coordination	2.4		1		1				1		1								1	1				50		1
	CVBG		TTL:	416.0		3	20	0	17	6	0	17	6	1	3	1	0	0	18	0	0	18	5	12	11	0	0	17	6	
			Ckts.	23		13%	87%	0%	74%	26%	0%	74%	26%	4%	13%	4%	0%	0%	78%	0%	0%	78%	22%	52%	48%	0%	0%	74%	26%	

Table 10 - Nominal Carrier Battle Group Communication Circuit Requirements

Ref #	Category	JCS PRI	Unit	Nomenclature	Data Rate (KBps)	Type Ops Duplex Full	Type Ops Duplex Half	Type Ops Simp	Avail On Call	Avail Full Pd	Connectivity Bd' Cast	Connectivity Net-ted	Connectivity Point/ Point/	Protection Requirements AS - Hemp	Protection Requirements Anti-Jam San	Protection Requirements Anti-Jam Tac	Protection Requirements Anti-Jam Nuc	Protection Requirements LPI LPD	Protection Requirements US Ctrl	Protection Requirements None	SATCOM Wide Band	SATCOM Nar Band	SATCOM Pro-tected	Service Provided Voice	Service Provided Data	Service Provided Video	Service Provided Comb	Duty Cycle <100%	Duty Cycle 100%	Req Mult
047	Comp Suppt	2E	ARG	*ARG Common*	2.4		1		1			1							1			1		1				50		1
049	Comp Suppt	2E	ARG	Close Air Support (CAS) Net	2.4		1		1			1							1			1		1				80		1
050	Comp Suppt	2E	ARG	ASW (Voice)	2.4		1		1			1							1			1		1				50		1
051	Comp Suppt	2E	ARG	ASUW (Voice)	2.4		1		1			1							1			1		1				50		1
052	Comp Suppt	2E	ARG	AAW (Voice)	2.4		1		1			1							1			1		1				80		1
053	Comp Suppt	2E	ARG	Information Ops (Voice)	2.4		1		1			1							1			1		1				80		1
054	Comp Suppt	2E	ARG	LAMPS Data Link	64		1		1			1							1			1			1			75		2
055	Comp Suppt	2E	ARG	UAV Control	32		1			1			1						1			1			1				1	2
058	Tac Warn / Inte	2F	ARG	*ARG SI Common*	2.4		1		1			1							1			1		1				80		1
059	Comp Suppt	2E	ARG	Cruise Missile Satellite DL	32		1			1		1							1			1			1			50		10
061	Comp Suppt	2E	ARG	CSEL	4.8		1		1			1							1			1			1			06		1
062	Comp Suppt	2E	ARG	ARGIXS	64		1		1			1							1			1			1				1	1
063	Comp Suppt	2E	ARG	LINK-16 (JTIDS)	64	1				1		1							1			1			1				1	1
064	Comp Suppt	2E	ARG	NTDS LINK-11	32	1				1		1							1			1			1				1	1
065	Comp Suppt	2E	ARG	SABER	4.8	1				1		1							1			1			1				1	1
066	Comp Suppt	2E	ARG	ARG SEAL / SOF Net	2.4		1		1			1							1			1		1				10		2
068	Tac Warn / Inte	2F	ARG	Remote Sensors (Afloat)	9.6		1		1			1							1			1			1			75		1
069	Tac Warn / Inte	2F	ARG	Remote Sensors (Ashore)	9.6		1		1			1							1			1			1			75		2
070	Comp Suppt	2E	ARG	EOD Net	2.4		1		1				1						1			1		1				80		1
071	Comp Suppt	2E	ARG	LCAC Coordination	2.4		1		1			1							1			1		1				80		1
076	*Comp Suppt*	*2E*	*ARG*	*ARG Cruise Missile MDU*	16		1		1				1	1									1		1				1	2
078	*Comp Suppt*	*2E*	*ARG*	*ARG SEAL / SOF Net*	2.4		1		1			1				1							1	1				10		1
082	*Comp Suppt*	*2E*	*ARG*	*ARG Secure*	2.4		1		1			1			1								1	1				80		1
090	*Comp Suppt*	*2E*	*ARG*	*ARG Coordination*	2.4		1		1				1		1								1	1				50		1
091	*Comp Suppt*	*2E*	*ARG*	*ARG Command*	2.4		1		1			1			1								1	1				50		2
ARG		TTL:		366.4		3	22	0	20	5	0	21	4	1	3	1	0	0	20	0	0	20	5	14	11	0	0	19	6	
		Ckts:		25		12%	88%	0%	80%	20%	0%	84%	16%	4%	12%	4%	0%	0%	80%	0%	0%	80%	20%	56%	44%	0%	0%	76%	24%	

Table 11 - Nominal Amphibious Readiness Group Communication Circuit Requirements

Ref #	Category	JCS Pri	Unit	Circuit Nomenclature	Data Rate (KBps)	Type Ops Duplex Full	Type Ops Duplex Half	Type Ops Simp	Avail On Call	Avail Full Pd	Connectivity Bd Cast	Connectivity Net/ Conf	Connectivity Point/ Point/	Protection AS - Hemp	Protection Anti-Jam Sanc	Protection Anti-Jam Tac	Protection Anti-Jam Nus	Protection LPI LPD	Protection US Ctrl	Protection None	SATCOM Wide Band	SATCOM Nar Band	SATCOM Pro- tect	Service Provided Voice	Service Provided Data	Service Provided Video	Service Provided Comb	Duty Cycle <100%	Duty Cycle 100%	Req Mult
001	Comp Suppt	2E	MEF	MEF Command 2	2.4		1		1			1				1						1		1				50		1
002	Comp Suppt	2E	MARFOR	ARFOR Comman	2.4		1		1			1							1			1		1				50		1
003	Tac Warn / Inte	2F	MARFOR	MARFOR Intel Net	2.4		1		1			1							1			1		1				50		1
007	Comp Suppt	2E	MAGTF	TF Command Net	2.4		1		1			1							1			1		1				50		1
008	Comp Suppt	2E	MEF	MEF Command 1	2.4		1		1			1							1			1		1				50		1
009	Comp Suppt	2E	MEF	MEF TAC 1	2.4		1		1			1							1					1				50		1
010	Comp Suppt	2E	MEF	MEF TAC 2	2.4		1		1			1							1			1		1				50		1
011	Tac Warn / Inte	2F	MEF	MEF Intel	2.4		1		1			1							1			1		1				50		1
012	Comp Suppt	2E	MEF	MEF Recon	2.4		1		1			1							1			1		1				50		1
013	Comp Suppt	2E	MEF	EF GCE Comman	2.4		1		1			1							1			1		1				50		1
014	Comp Suppt	2E	MEF	F TACAIR Comm	2.4		1		1			1							1			1		1				50		1
015	Comp Suppt	2E	MEF	EF RAD BN (DSU	2.4		1		1			1							1			1		1				50		1
025	Comp Suppt	2E	CMEF	CMEF Command 1	2.4		1		1			1							1			1		1				50		1
026	Comp Suppt	2E	CMEF	CMEF Command 2	2.4		1		1			1							1			1		1				50		1
027	Tac Warn / Inte	2F	CMEF	CMEF Intel	2.4	1			1			1							1			1		1				50		1
028	Comp Suppt	2E	CMEF	EF TACAIR Comm	2.4		1		1			1							1			1		1				50		1
031	Comp Suppt	2E	MSS	Satellite Service	2.4		1		1				1						1			1		1				5		100
016	Comp Suppt	2E	MEF	SABER	4.8		1		1			1							1						1				1	1
			TTL Kbps	48		1	17	0	18	0	0	17	1	0	0	1	0	0	17	0	0	16	0	17	1	0	0	17	1	
			TTL Ckts	18		6%	94%	0%	100%	0%	0%	94%	6%	0%	0%	6%	0%	0%	94%	0%	0%	89%	0%	94%	6%	0%	0%	94%	6%	

Table 12 - Marine Corps Communication Circuit Requirements

APPENDIX B - MUS REQUIREMENT DEFINITIONS

The following is a paraphrased list of Mobile User Study (MUS) requirements definitions. All terms are used based upon general definitions provided in the USCINCSPACE MILSATCOM Capstone Requirements Document (CRD), then amplified to provide clarification as they relate to the MUS effort. For further amplification see the CRD. As of this writing the MUS Prioritized Requirements document has not been released for use outside of the MUS participants. Further refinement of these requirements is necessary to support test and evaluation of system performance. [Ref. 21]

- **Assured Access**: The certainty that the requisite amounts of services are immediately available and accessible for use when and where needed in accordance with priorities set by the operational commander, and that they can be quickly reconfigured to meet the demands of the warfighter's operational environment. It is recognized that not all users can be accommodated all of the time. Instead, a prioritized set of users should be able to gain access when that access is both allowed and necessary

- **Netted Communications**: A communication topology that allows multiple users to communicate on a common data stream. This type of circuit is normally half duplex and full period. Manual or automated processes should be established to control access and transmission permissions. There shall be no predetermined number of users or terminals on a net.

- **Communications on the Move**: This capability shall provide the ability of the warfighter to move and talk at the same time. This capability enables the user to have voice and data communications in any natural environment to include double canopy jungle, urban, rain, and sea environments.

- **Jointly Interoperable Communications**: This is the ability of systems, units, or forces to provide information services to, and accept information services from other systems, units, or forces. This information must be exchanged to enable them to operate more effectively together. The ability to share information promotes the

common interpretation and understanding of the battlespace fundamental to ensuring unity of effort and synchronization of action. The goal for the entire military grid is to provide warfighters and their systems the ability to exchange and understand information unimpeded by differences in connectivity, processing, language, or interface characteristics.

- **Worldwide Coverage**: Encompasses 24 hour per day communications service coverage from 65^0 North to 65^0 South latitude without gaps in geographical coverage.

- **Point to Point Communications**: This is a topology that supports communications between two single terminals. This type of link is typically full duplex, on call, and may support half-duplex and full period communications. Point to point communications are required to support voice, data, or video to support VIP, Special Operations Forces (SOF), and control of UAV missions.

- **Broadcast Communications**: This is a full period, simplex link that supports a single transmitter providing information to multiple receiving terminals. Broadcast is primarily used for transmission of battlespace awareness data and intelligence information to users who can join the broadcast at any time.

- **Polar Coverage**: This includes 24 hour per day communication service for that area of the Earth above 65^0 North and below 65^0 South latitude. Communications service is primarily directed at the northern polar region for reasons of national security, but some requirements do exist in the southern polar region. A Polar SATCOM Operational Requirements Document provides specific requirements in these regions.

APPENDIX C - SATCOM TERMINAL LAYDOWN

The following pages contain tables listing current and planned SATCOM terminal population. Terminals are divided by frequency operating range and purpose. Future acquisition for Naval forces are listed by service. Finally, a breakdown of planned acquisition and disposal numbers is provided. This information is excerpted from an informal Terminal Laydown database maintained by the CNO/N63 office. [Ref. 36]

Terminal Migration Plans - Current & Near-Term						Estimated Fielding Schedule																
	Terminal Designator	Terminal Type	USN	USMC	Prior	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14
Airborne UHF	ARC-187 & ARC 210	Airborne UHF Terminal	800	0	800											-332	-331	-137				
	ARC-187	Airborne UHF Terminal			0			+53	+53	+75	75	74	74	74			-53	-62	-86	-86	-34	-34
	AN/USC-42(V)1	Airborne Mini-DAMA	98		30	15	+15	+15	+15	+8									-15	-15	-15	-15
	AIT	Integrated DAMA/ANDVT Airborne UHF Terminal			0			+53	+53	+75	+75	+74	+74	74			-53	-53	-75	-75	-74	-74
	ARC-171	Airborne UHF Terminal			400	-40	-40	-40	-40	-40	-40	-40	-40	-40	-40							
Manpack / Handheld UHF	AN/PSC-5 (EMUT) (SPITFIRE)	Manpack			1932	381									-932	-1000	-578	-381		EOL		
	AN/PSC-5 (EMUT)	Manpack	700	1000				800	900									-800	-900			
	EMUT (PSC-5) or Follow-On	UHF Manpack			0		400	400	400	400	400	446			-400	-400	-400	-400	-400	-446		
UHF Shore	WSC-3	Shore	5		5		-5															
	Shore DAMA	Shore	5		0		5															-2
	VICS	Shore	55		55										-11	-4	-8	-13	-8	-4	-7	
UHF Shore Mobile	WSC-3	Shore Mobile	-11		11										-11							
	WSC-3	Shore Mobile	-298		574		R/U	R/U	R/U	R/U												-38
	WSC-3	ground fixed			25										-25							
UHF Ship	WSC-3		-3053	-30	391				-100	-100	-100	-81										
	Ship DAMA - DMR	Includes range from single DAMA for Small ships to Hex DAMA for Carriers	391		13	13	5	80	108	81	61	61	9							-13	-13	-6
	AN/USQ-122(V)1	Ship, Trans	491		75	39	113	120	110	34												

Table 13 - UHF SATCOM Terminal Laydown (continued on next page)

Terminal Migration Plans - Current & Near-Term						Estimated Fielding Schedule																
	Terminal Designator	Terminal Type	USN	USMC	Prior	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14
Sub UHF	AN/USC - 42(V)	Sub-Mini DAMA	238		18	24	12															
UHF CTT/JTT All Platforms	AN/USC-45 Hybrid 3-Channel (CTT-H3)	All - Total			0	56	56	110	110	80	80											
	CTT/JTT		245	30	14		5	33	49	77	57	30										
	USC-65 CTT/Hybrid				300										-187	-113						
	AN/USR-6 CTT-H R(2) Rx-only 2-channel				186																	-86
	AN/USR-6 CTT-H R3 Rx-only 3-channel				86																	-40
	ASC-19	Abn SIOP			111								-22	-23	-22	-22	-22					
	FRC-178	fixed			80								-25	-25	-30							
	USC-38	transportable			7								-4	-3								
	USQ-101 (V)4,7	tactical Rx only			172										-172							
	USR-5	tactical Rx only			82										-82							
	USR-6	tactical, 3 channel, Constant Source			23										-23							
MATT	Multi Mission Advanced Tactical Terminal (MATT)	Airborne, Ground mobile			152											-50	-52	-50				
	MATT	air tactical terminal, RX only			100										-25	-25	-25	-25				
	GSC-44	Fixed	1		1								-1	EOL								
	AN/SSR-1A	Ship & Shore	688	36	723	-62	-147	-147	-147	-147	-73											
	SUCCESS Radio	Highly Transportable			60										-60							
	D-1324 modem				113	183																
5 KHz	DMR						226	73	100	276	321											
	PSC-5 manpack				180	96																
UHF Totals, BY					6,426	436	419	1,467	1,511	493	806	654	65	57	-2,020	-1,946	-1,822	-1,911	-1,404	-639	-148	-294
UHF Totals, Cumulative					6,426	6,862	7,271	8,738	10,299	10,732	11,237	11,791	11,856	11,913	9,893	7,947	6,035	4,514	3,090	2,391	2,348	1,954

Table 14 - UHF SATCOM Terminal Laydown (continued from previous page)

Terminal Migration Plans - Current & Near-Term						Estimated Fielding Schedule																
	Terminal Designator	Terminal Type	USN	USMC	Prior	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14
SHF Airborne	ASC-24	Airborne			5									-2	-2	-1						
SHF Large Fixed	AN/FSC-78	Fixed Facility			16	MU5	MU1												-3	-7	-5	-1
	FSC-78	fixed	4		4																-4	
	FSC-78	fixed			6																-6	
	AN/FSC-79 (HTMT)	Fixed			3	MU1													-1	-1	-1	EOL
	AN/FSC-79	Fixed	5		5												-5					
	FSC-97 SCTIS	fixed	2		2								-1	-1								
	FSC-97 SCTIS	fixed			7								-7									
	AN/.GSC -39 (V)1,2	Fixed Facility, Transportable			15	MU3	MU1												-6	-5	-3	-1
	AN/.GSC -39 (V)1,2	Fixed Facility, Transportable	4		4	MU3	MU1															-4
	GSC-39 (v)2				5								-5									
	AN/GSC-49 Contingency				21											-1	-1	-1	-2	-14	-5	
	GSC-49 JRSC (v)1,2,3				16												-16					
	AN/GSC - 52 (V)1,2	Fixed Facility, Transportable			39		MU1	MU5	MU9	MU12	MU12											
Ground Transportable	AN/GSR-42 SCTR	Transportable			5								-5									
	AN/GSR-42 SCTR	Transportable	1		1							-1	EOL									
	AN/TSC-85 B(V) 1,2	Transportable			77	-20	-23		-24	EOL												
	TSC-85B (v)2			15	15			-3	-3	-3	-3	-3										
	TSC-85B (v)2				19	MU	MU	MU					-3	-4	-4	-4	-4					
	AN/TSC-93B(V)1,2	Transportable			127	-12	-12	-28	-32	-24	EOL											
	TSC-93B (v)2		5	41	46				-9	-9	-9	-9	-10									
	TSC-93B (v)2				33	MU	MU	MU					-6	-6	-7	-7	-7					
	TSC-94 (v)1,2				68	MU	MU	MU					-13	-13	-14	-14	-14					

Table 15 - SHF SATCOM Terminal Laydown (continued on next page)

Terminal Migration Plans - Current & Near-Term					Estimated Fielding Schedule																	
	Terminal Designator	Terminal Type	USN	USMC	Prior	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14
Ground Transportable	LST-8000 (v) 3-6				33	MU	MU	MU					-6	-6	-7	-7	-7					
	ST-Van	ground transportable			2	mu							-1	-1								
	LMST	ground transportable			+15		+12	+12	+13	+12	12			.	-15	-12	-12	-13	-12	-12		
	SCT-20	Fixed Facility, Transportable			2			-2														
	FSC-111 ISST	ISST ICBM LCC terminal			74								-22	-22	-30							
	GT-2008 SURTASS	Transportable Shore	4		4						-2	-2										
SHF Ship	AN/WSC-6(V)2&4	Large Shipborne, Mobile	28		28																	-9
	AN/WSC-6	Large Shipborne, 7' Antenna	23			10	6	7														
	AN/WSC-6	Large Shipborne, Dual Channel Upgrade	30		4	6	8	12														
(Sub-SHF: See EHF)	AN/WSC-6(V)X	Small Shipborne, Mobile	112		0	3	1	14	10	12	14	16	14	14	14							
SHF HMWWV	STAR-T	Highly Transportable			4	7	11	26	32	39	34						-4	-7	-11	-26	-32	-39
	STAR-T	Highly Transportable		60	0			4	8	12	13	23										
	PT3				6																	
SHF Totals, BY					711	-6	3	44	-5	39	59	24	-65	-41	-65	-46	-70	-21	-35	-65	-56	-54
SHF Totals, Cummulative					711	705	708	752	747	786	845	869	804	763	698	652	582	561	526	461	405	351

Table 16 - SHF SATCOM Terminal Laydown (continued from previous page)

Terminal Migration Plans - Current & Near-Term						Estimated Fielding Schedule																
	Terminal Designator	Terminal Type	USN	USMC	Prior	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14
	EHF																					
EHF Airborne	ARC-208 (v)1,2	M* airborne CP	17		17																	
	ARC-208 (v)1,2	M* airborne CP			22																	
EHF Ground Fixed	FRC-181 (v)1	M* gnd CP	2		0																	
	FRC-181 (v)1,2	M* gnd CP			37					-7	-7	-6	-6	-7								
	AN/FRC-181 (V) 1 (EHF & UHF GNDCP)	Fixed			3																	
	AN/USC-38(V)3	NESP Shore	73		38			1	3	3	20	4	4									
EHF Transportable	AN/TRC-194 (V) 1 (EHF & UHF GNDCP)	Transportable			3																	
	AN/TRC-194 (V) 1 (EHF & UHF GNDCP)	Transportable	1		1																	
	TRC-194 (v)1, 4	M* transportable CP			22							-4	-4	-5	-5	-4						
	AN/TRC-194 (V) 2 (EHFOnly)	Transportable			1																	-1

Table 17 - EHF SATCOM Terminal Laydown (continued on next page)

Terminal Migration Plans - Current & Near-Term					Estimated Fielding Schedule																	
	Terminal Designator	Terminal Type	USN	USMC	Prior	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14
HMWWV EHF	SMART-T	Highly Transportable			0	20	23		47	67	78									-20	-23	
	SMART-T	SMART-T, transportable	4		0			+2	+2													-2
	SMART-T	SMART-T, transportable			0	+0	+9	+0	+20	+21	+36										-9	
Sub EHF (SHF)	AN/USC-38(V)1	NESP Sub	74		34	5	11	2	5	5	4	4	3									
	Sub HDR	SHF/EHF Sub Terminal	43					6	9	14	14	14										
EHF Ship	AN/USC-38(V)2	NESP Large Ship	61		70	4	6	6	5	8												
	AN/USC-38(V)2	NESP Small Ship	191		54	4	4	9	5	10	6											
Manportable/ Manpack	SCAMP BLOCK I	Manportable			0	57	93									-57	-93	EOL				
	SCAMP BLOCK I POLAR mod	Manpack			0	EMDE	PS															
	SCAMP BI	SCAMP, Block I, ground			0		+55	+99					-77	-77								
EHF Totals, BY					302	90	201	125	96	121	151	10	-82	-89	-5	-61	-93	0	0	-20	-32	-3
EHF Totals, Cummulative					302	392	593	718	814	935	1,086	1,096	1,014	925	920	859	766	766	766	746	714	711

Table 18 - EHF SATCOM Terminal Laydown (continued from previous page)

Terminal Migration Plans - Current & Near-Term					Estimated Fielding Schedule																		
	Terminal Designator	Terminal Type	USN	USMC	Prior	98	99	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14
	Commercial																					
	INMARSAT	Inmarsat Aero-C			100			+100	100	100				-100	-100	-100	-100					
	INMARSAT	Inmarsat Aero			0			+100	+100	+100	+100	+100	+100									
	INMARSAT	Inmarsat Std A	242		242		-38	-66	-33	-32	-32	-41										
	INMARSAT	Inmarsat Std B	235		44	24	67	36	32	32							-38	-66	-33	-32	-32	
	INMARSAT	Inmarsat Std B			87													-43	-44			
	INMARSAT	Inmarsat Std C	58		58													-25	-25			
	INMARSAT	Inmarsat Std M	30		10	7	10	3							-8							
	INMARSAT	Inmarsat Std M			30													-15	-15			
	ORBCOMM	ORBCOMM			0		+50	+50	+50	+50	+50	+50	+50	50	-50	-50	-50	-50	-50	-50	-50	-50
	C/Ku	C/Ku VSAT			36													-18	-18			
	TVRO	TVRO	11		11	-11																
	TV-DTS	TV-DTS	220		0	110	110															
	Ku JBS	Shipborne	21		21										-21							
	PCS/MSS	PCS/MSS	750			75	75	75	11	200	300	14										
	CWSP	Commercial Wideband	15		15																	
	ATS	Commercial Wideband	206			47	48	48	48	15												
Comm Totals, BY					654	252	322	346	308	465	418	123	150	-50	-179	-150	-188	-217	-185	-82	-82	-50
Comm Totals, Cummulative					654	906	1,228	1,574	1,882	2,347	2,765	2,888	3,038	2,988	2,809	2,659	2,471	2,254	2,069	1,987	1,905	1,855

Table 19 - Commercial SATCOM Terminal Laydown

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